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Eelgrass (*Zostera marina* L.) Stressors in Puget Sound

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Summary

Recent studies have shown that seagrasses are declining globally. There is widespread concern that eelgrass (*Zostera marina* L.) is significantly less abundant than historically in Puget Sound. It is assumed that stressors caused by human activity have caused most of the loss, though the contribution of natural variation to eelgrass declines is unknown. The intensity and type of disturbances affecting eelgrass are changing over time as population growth, land use, climate, and regulatory actions change in the Puget Sound region and affect eelgrass habitat. Decisions regarding the most effective and efficient management actions suffer from critical uncertainties about the intensity, extent, and reversibility of stressors affecting eelgrass. Understanding the relative importance of various stressors and their interactions and anticipating their future impacts will help drive research and management actions to restore eelgrass.

The objective of this report is to provide a technical summary and ranking of stressors affecting eelgrass in Puget Sound. The ranking process is designed to help inform target setting for eelgrass area and health and to help prioritize eelgrass management and research activities. We begin with a conceptual model linking eelgrass structure and health to stressors and controlling factors, accompanied by a discussion of general research on eelgrass. Many stressors interact with each other, either by increasing or compensating for the effects of others, leading to effects that may be hard to predict or difficult to attribute to individual stressors in cases of eelgrass decline. Genetic variation between subpopulations adds complexity to the management implications of our research, as conditions affecting eelgrass at specific sites and the adaptations of eelgrass at those sites may be unique. The reversibility of particular stressors or their impacts should also be considered in an analysis of stressors, as ramifications for management or prevention may vary depending on whether a particular stressor can be removed once present. There are several types of uncertainty about each stressor that we incorporate into our assessment and ranking process.

A number of global studies focusing on seagrasses have concluded that seagrasses are in decline. These studies identified a set of principal stressors potentially causing the declines. They highlight nutrient runoff and other effects on water quality as well as climate change impacts, particularly sea-level rise, as being of the highest threat to seagrasses worldwide. The studies also conclude that there is considerable uncertainty associated with the mechanisms, scales, and other aspects of the effects of stressors on seagrasses.

We summarize a number of case studies from Puget Sound and nearby coastal areas. Many of these focus on direct and localized human-driven stressors to eelgrass such as aquaculture, construction, and overwater structures which affect the health and survival of existing eelgrass beds and mitigation transplant projects. The stressors observed to have the greatest impact on eelgrass were those that directly affected substrate (construction, boat activity, etc.) and shading from overwater structures and macroalgal blooms. Algal blooms also prevented the recovery of eelgrass beds after other stressors were removed. Most studies were of small areas but observed multiple, interacting stressors.

We spatially quantify stressors where data are available, including historical records. In particular we note trends in population size, land use, impervious surfaces, shoreline armoring, overwater structures, water quality, and sediment contamination. These results are summarized for the same regions used for eelgrass monitoring to allow for comparisons of trends in stressors with eelgrass trends. Overall

population growth and direct disturbance of the shoreline has increased considerably over time. Historically eelgrass would have been more heavily affected by logging and agriculture, while pressures linked to urban and suburban land use would be greater in the present day. Stressors are likely to vary considerably around Puget Sound as many are directly linked to human population concentrations in urban centers, while others are linked to agriculture and resource extraction that may be more prevalent in areas with lower population densities. Overwater structures and water quality issues both exhibit considerable variation in their intensity in different regions of the Sound.

In order to better distinguish the effects of anthropogenic stressors from natural variability in eelgrass populations, we describe a process for quantifying natural variability in eelgrass beds that could be used to identify eelgrass sites that are stressed beyond natural fluctuations in density or cover. While data are not currently sufficient to fully apply this approach, we demonstrate how it could be used on some sample data sets.

We summarize our stressor analysis in a ranking table that includes assessments of magnitude, spatial and temporal extent, reversibility, and trend and the information available about these factors and produces a stressor ranking and uncertainty ranking score for each identified stressor. We also summarize results from the case study and global studies analyses in the table. From this ranking we identify three groups of stressors. The first group is estimated to have high present or future impacts on eelgrass, with only limited information available on the extent of those impacts. This group includes stressors that are related to water quality and light availability (sea level and temperature rise, suspended sediment, nutrient-driven harmful algal blooms, contaminants, disease and freshwater input) and shoreline armoring. These stressors should be high priorities for research and may also be opportunities for management and mitigation. The second group is expected to be lower threats to eelgrass but with significant uncertainty (invasive species, aquaculture, organic matter/sulfides, boat grounding and anchoring, propeller wash and boat wake, overfishing, and bioturbation). For this group, further study will be necessary to understand the extent of effects on eelgrass and potential for improvements in eelgrass health and cover following reduction in stressors. The research needs for these stressors may be less, but they are still potentially effective management targets. Finally, the third group consists of those stressors that are known threats and relatively well researched (overwater structures, dredging/filling, and construction). These are important for management, but need less research attention at this time.

We conclude with recommendations for the DNR stressor-response program, recommendations for management actions for protecting and restoring eelgrass according to our ranking of stressors, and general recommendations for eelgrass research for the broader community in Puget Sound. These include the development of a numerical model to be linked with the monitoring program, further characterization of sites that have lost eelgrass, focus on land use and climate change, and development of a reference system study site to better understand natural population variability, viability, and resilience.

Acknowledgments

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Acronyms and Abbreviations

ANOVA	analysis of variance
cps	Central Puget Sound sampling region
CV	coefficient of variation
DNR	Washington State Department of Natural Resources
ft^2	square foot (feet)
GIS	geographic information system
GIRAS	Geographic Information Retrieval and Analysis System
ha	hectare(s)
hdc	Hood Canal sampling region
HUC	hydrologic unit code
km	kilometer(s)
m	meter(s)
m^2	square meter(s)
nps	North Puget Sound sampling region
PNNL	Pacific Northwest National Laboratory
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
sjs	San Juan sampling region
sps	South Puget Sound sampling region
str	Straits sampling region
swh	Saratoga-Whidbey sampling region
SVMP	Submerged Vegetation Monitoring Project
TMDL	Total Maximum Daily Load
USGS	United States Geological Survey
WDFW	Washington Department of Fish and Wildlife

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1.0 Introduction

Eelgrass *(Zostera marina)* is a perennial marine plant found throughout Puget Sound that provides a valuable source of food and shelter for many marine species while reducing erosion and improving water quality. It is suspected that the extent and abundance of eelgrass in Puget Sound has declined significantly since the 1800s. While eelgrass can be significantly affected by natural climate variability, much of its decline is assumed to be caused by anthropogenic disturbance — a result of local actions and broader regional and global climate change. As pressures stemming from population growth and climate change intensify in the future, eelgrass will likely decline further if directed management and restoration actions are not taken. Considerable uncertainty about the trends in eelgrass density and abundance over time, the extent and impact of stressors, and the effectiveness of management actions complicates decision making about eelgrass restoration and recovery. To help address these uncertainties, we have conducted a review of stressors known or expected to affect eelgrass in Puget Sound in the past, present, and future. The Washington State Department of Natural Resources (DNR) conducts the eelgrass monitoring component of the Puget Sound monitoring program. Under this component, the DNR investigates issues that arise with eelgrass through their Eelgrass Stressor-Response Project and has conducted research to explain recent, rapid losses of eelgrass meadows in some areas of Puget Sound. In 2010, the DNR requested our assistance in evaluating and ranking eelgrass stressors in Puget Sound. The primary objective of our report is to provide a prioritized list of eelgrass stressors based on an analysis of past, present and future stressors.

1.1 Background of the DNR Eelgrass Programs

The Washington State DNR is steward of 2.6 million acres of state-owned aquatic land. Because eelgrass (*Zostera marina* L.) is an important component of the public and private nearshore aquatic lands in greater Puget Sound, the DNR manages these aquatic lands for the benefit of current and future citizens of Washington State. The State of Washington gives eelgrass beds special protections: the Washington Department of Fish and Wildlife (WDFW) has designated eelgrass areas as habitats of special concern, and the Washington State Department of Ecology has designated eelgrass as critical habitat under its statutory authority in implementing the state Shoreline Management Act.

As part of their stewardship, DNR has monitored eelgrass annually in Puget Sound since 2000. This effort has yielded a better understanding of both the natural variation in eelgrass and identification of areas that have shown both major declines and significant increases. This has allowed DNR to develop hypotheses about causes of these changes and to initiate investigations into these hypotheses. In 2005, the Nearshore Habitat Program within the DNR initiated the Eelgrass Stressor-Response Project in follow-up to a panel review of DNR's annual eelgrass monitoring project in 2003. The panel specifically recommended the initiation of process studies (field and laboratory experiments and modeling) to identify and understand the causal factors responsible for the patterns and trends detected by the monitoring project. By 2005 DNR had completed five years of monitoring. Supported by the observations of other scientists in the region, monitoring results clearly identified two geographic areas of eelgrass decline that were a cause for concern: Hood Canal and shallow embayments within the San Juan Archipelago. The goal of the new Eelgrass Stressor-Response Project was to identify eelgrass stressors causing these particular declines to inform the development of management strategies.

Fieldwork led by DNR began in 2006 with several discrete studies that were intended to provide a background for later work. This initial work phase relied on collaborations with researchers at the University of Washington (at its Friday Harbor Laboratory and the Seattle campus) and the Coastal and Marine Geology Group of the U.S. Geological Survey. Initial conceptual models were developed by DNR and their collaborators for stressors in Hood Canal and in the shallow embayments of the San Juan Archipelago to guide the stressor studies, which investigated carbon/nitrogen isotopes, eelgrass photosynthesis, eelgrass genetics, high-resolution bathymetry, and potential effects from the Fraser River plume (Dowty et al. 2007).

A second phase of work led by DNR began in 2007 with an intensive focus on Westcott Bay, San Juan Island. This shallow embayment had a rapid and nearly complete eelgrass loss around 2003. The research had two main components that spanned the 2007–2009 period. One focused on the continuous measurement of environmental parameters at several stations across the bay. The other focused on the performance of eelgrass transplants, also at several stations across the bay. The initial working hypothesis was that high levels of water column turbidity, largely associated with tidal resuspension, led to lower submarine light levels and eelgrass decline.

Two main findings were derived from the work conducted in Westcott Bay. First, there appeared to be ample light for eelgrass survival (Dowty and Ferrier 2009). This undermined the high-turbidity hypothesis and led to the formulation of other hypotheses regarding other possible stressors. The second finding was that 4 to 6 years after the eelgrass loss, the Westcott Bay environment still did not support eelgrass growth and persistence (Schanz et al. 2010). The lack of natural recolonization eliminated the possibility that the mortality of the existing population in 2003 was caused by a pulsed disturbance that did not continue to affect the bay.

The DNR Eelgrass Stressor-Response Project has continued to closely monitor Westcott Bay for eelgrass recolonization and changes in the small remnant population that has survived. New strategies are currently being formulated to drive the future direction of the project.

1.2 Purpose and Scope

The purpose of this project was to provide a technical summary of stressors (with related uncertainties) to inform target setting for eelgrass area and health in the future with a greater degree of certainty than is presently possible. To this end, our primary objective was to identify and rank stressors affecting eelgrass, with respect to current conditions in Puget Sound and how the stressors may be changing in importance over time. Because the relative importance of stressors may depend upon many factors (e.g., spatial and temporal extent, intensity of effect, reversibility, interactions with other stressors), we took several approaches to understanding the stressors and the uncertainty involved. Data specifically evaluating most stressors affecting eelgrass in Puget Sound are limited, but we used a variety of sources to compile information from controlling factors research, global seagrass studies, local case studies, monitoring, spatial data sets, and expert opinion. We also developed recommendations for research to address the critical uncertainties. This information is intended to provide an objective basis for focused research that will result in improved management decisions regarding the conservation of existing eelgrass meadows and expansion of eelgrass distribution in Puget Sound.

We evaluated stressors using multiple lines of evidence based primarily on expected threat to eelgrass and level of knowledge about these threats. Among the final products is a table in which we summarize the priorities along with the factors that contributed to the prioritization. To develop the prioritized list of stressors, we used the following information:

- A conceptual model that shows basic links between potential stressors and factors that control eelgrass presence, abundance, and growth.
- Definitions of uncertainties associated with the knowledge base supporting stressors.
- A review of recent global and local assessments of threats to seagrasses.
- Case studies from the region on eelgrass changes, restoration and natural variation.
- A GIS-based spatial analysis of past, present and future potential stressors to eelgrass in Puget Sound.
- A method to assess natural variation in eelgrass meadows.

We then synthesized the information above into a simple table for scoring the various stressors. We summarized stressors into three categories based on degree of threat and uncertainty and provided general recommendations on eelgrass stressor research and strategies that could focus efforts to support the goal of a 20% increase in eelgrass by the year 2020.

1.3 Report Contents and Organization

We begin this report with a conceptual model of eelgrass and its controlling factors and stressors. This is accompanied by a discussion of controlling factors research, stressor interactions, genetic variability, and reversibility of stressors. We then provide a brief summary of stressors identified in global seagrass studies, including a table of stressors identified in these studies and terminology used by different authors. Following is the results of a case study analysis with a summary of the studies examined, their location and scale, the stressors identified and the strength of evidence for their effect on eelgrass. Details of these case studies can be found in Appendix A. The spatial quantification of stressors presents the results of analysis of available spatial data by eelgrass sampling region, including population and land use change, impervious surfaces, shoreline armoring and overwater structures, and water and sediment quality and contamination. Additional maps and summary tables from this analysis are located in Appendix B. The next section contains a description of a method for quantifying natural variability, with an example of how the calculations would be employed. We summarize our analysis and expert opinion in a stressor ranking table, followed by a discussion of the results categorized into three groups of stressors with similar threat and uncertainty levels. Finally, we offer recommendations for future research and a summary of management actions.

2.0 Eelgrass Conceptual Model and General Stressors Research

Building on previous field, laboratory, and modeling work, we developed a working draft conceptual model of eelgrass (Figure 2.1) to aid in our analysis and discussion of eelgrass stressors. As shown in the figure, *controlling factors* are elements that directly drive eelgrass structure and health. For most of the controlling factors, a range of values (e.g., light) or types (e.g., substrate) are tolerated or required by eelgrass. When controlling factors range beyond those tolerances, eelgrass is adversely affected. Conceptual model elements defined as *stressors* are generally detrimental to eelgrass at any level. Stressors may act upon eelgrass directly (e.g.**,** disease, contaminants) or by altering controlling factors to extents that have negative effects upon eelgrass (e.g.**,** light attenuation from overwater structures or suspended sediments)**.** The tolerances for controlling factors and stressors may vary among subpopulations, as addressed below; therefore we show that interactions in the model will be mediated by local adaptation.

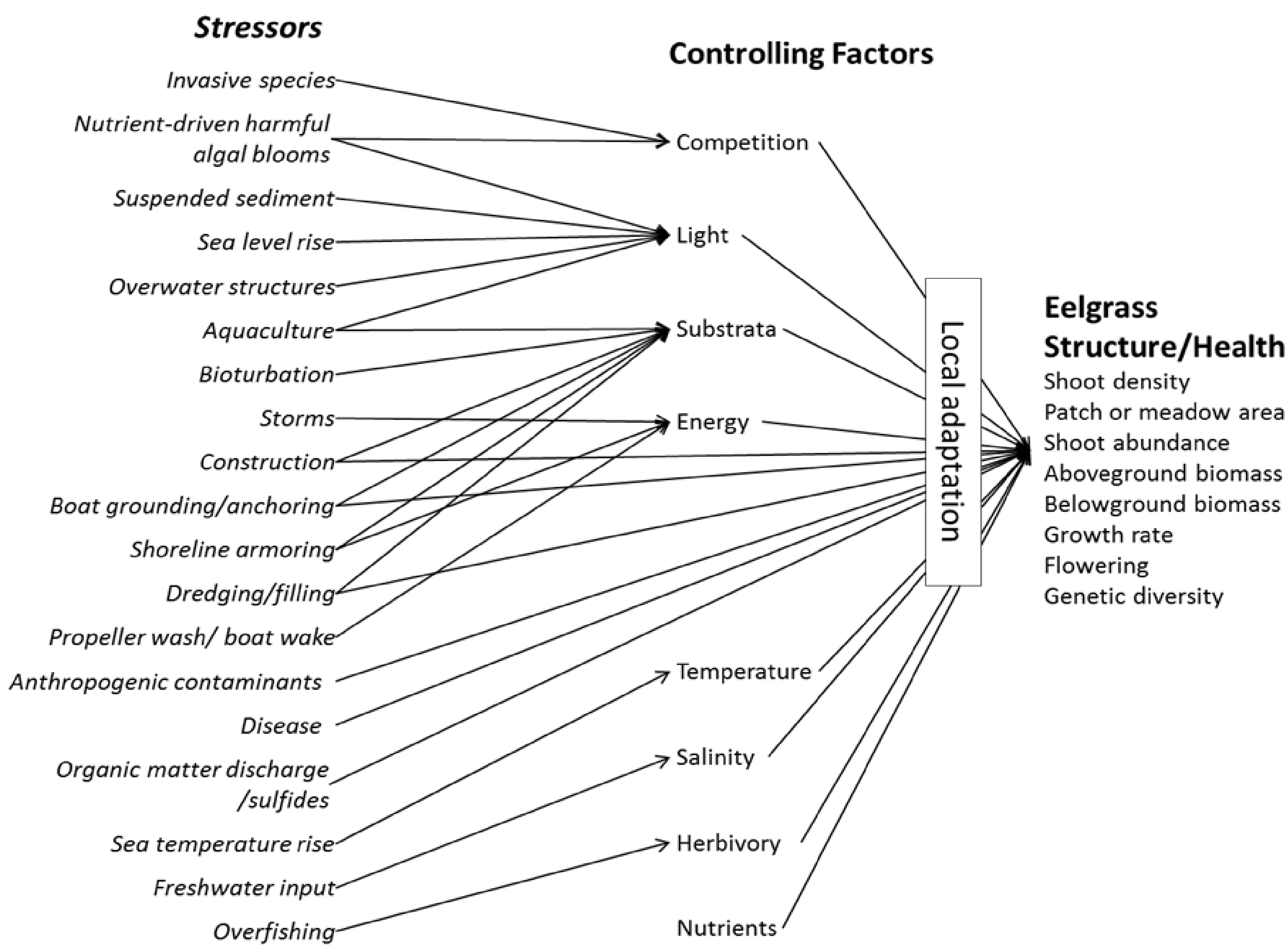


Figure 2.1. Working Draft of the Eelgrass Conceptual Model Based on Past Models and Our Present Review of Stressors and Linkages

The model is expanded and modified from a conceptual model of eelgrass habitat requirements (Thom et al. 2005). The understanding of environmental requirements is based on early work by Phillips (1984) as well as more recent field studies and experiments. Thom (1996) and Thom et al. (2001a,b; 2003; 2008a) and references therein report the empirically determined ranges of controlling factors suitable for eelgrass growth. We expanded the conceptual model based on an extensive review of stressors developed for the Gulf of Mexico Regional Collaborative (Judd et al. 2007), which focused on assessing stressors from various sources on submerged aquatic vegetation in the Gulf of Mexico. The full list of stressors and how they affect controlling factors, processes, functions, etc., is available at http://www.gomrc.org/sav/conceptual_model.html.

Individual stressors can have multiple effects on eelgrass. For example, ferry terminals not only shade eelgrass, but also result in potential damage because of propeller wash and scour, construction and maintenance, and bioturbation driven by enhanced habitat for some species (Thom et al. 2005). Not all of these effects, taken individually, would have strong impacts on eelgrass, but in combination multiple sublethal stressors can cause significant loss of eelgrass.

Stressors can interact in multiple ways, with effects sometimes intensified by the presence of other stressors and, in other cases, reduced or reversed. For example, changes in both temperature and salinity condition have been described as being necessary for outbreaks of wasting disease elsewhere (Short et al. 1986; 1988). However, the relative roles and levels of change in salinity and temperature that will initiate wasting disease to a point where it significantly damages a population are not known for Puget Sound. Climate change effects such as increased carbon dioxide can be positive for seagrass growth, but also increase the growth of epiphytes and resulting shading effects (Duarte 2002). Eelgrass may be able to redistribute itself to compensate for sea-level rise, but not if armoring or other shoreline modifications restrict the available space (Short and Neckles 1999). Because of the sheer number of interactions, we do not show these interactions in Figure 2.1.

Phenotypic and genotypic variation is not well studied in the region, but may have a significant role in the relative response of populations to stressors (Ehlers et al. 2008). Our observations in mesocosms, previous studies in Puget Sound (Backman 1991; Wyllie-Echeverria et al. 2010) and studies elsewhere (e.g., Muniz-Salazar et al. 2005) show that eelgrass adapt to local conditions. Local adaptation may lower subpopulation genetic diversity while increasing diversity overall in Puget Sound. This fact makes general assessment of the effects of stressors more difficult, because local adaptations may make local populations more or less vulnerable to changes in conditions at a site. For example, in assessing climate change effects, a rise in sea level and temperature may have variable effects throughout the Sound depending upon both the range of conditions currently experienced at a site and the adaptation of the eelgrass present there.

Another characteristic of stressors that will determine the role of eelgrass decline and recovery is the reversibility of stressors and/or their impacts. On one level, the management implications of a particular stressor depend on the practicality of removing or reversing the stressor itself: can it be stopped or removed (e.g., nutrient runoff, boat activity), would it require extensive intervention (e.g., removal of armoring and restoration of substrate), or is it not directly or locally manageable at all (climate effects)?

On another level, the presence and density of eelgrass itself may determine the impact of a stressor through positive feedbacks that reinforce eelgrass presence (van der Heide et al. 2007). Eelgrass has been found to improve water quality through nutrient uptake and sediment stabilization (Carr et al. 2010; van der Heide 2011) and dilution of toxic substances such as reduced nitrogen (Moore 2004; van der Heide et al. 2008, 2010). Sufficient densities of eelgrass have also been found to exclude macroalgae (Nelson and Lee 2001), modify sediments (van Katwijk et al. 2010), and reduce wave and current energy (Bos and van Katwijk 2007), all of which can enhance eelgrass survival and recruitment. Consequently, loss of eelgrass can alter the environment sufficiently to inhibit the recolonization of eelgrass, and restoration must occur on a large enough scale to allow positive feedbacks to resume and restored beds to persist, or if environmental conditions are altered beyond what would be needed for a self-reinforcing population.

2.1 Uncertainty in Eelgrass Stressor Analysis

Many uncertainties are associated with the eelgrass conceptual model. The magnitude and spatial and temporal extent of the stressors vary, and few of these factors are easily quantified. For example, the location and suspected effect of overwater structures on eelgrass can be estimated relatively easily using various geographic information system (GIS) data associated with potential eelgrass habitat distribution. However, the spatial extent and magnitude of stressor impacts, such as algal blooms, storms, sea-level rise and bioturbation, are less easily estimated and may be even more difficult to project into the future.

Uncertainty can be roughly divided into two categories: epistemic (and structural) uncertainty, and uncertainty arising from natural variability. Epistemic uncertainty reflects the state of knowledge about how a system operates, such as the shape and strength of relationships between ecosystem components, interactions across relationships, or how relationships change with temporal or spatial scale. This can also include knowledge about the current and historical status of the system, e.g., distribution and genetic diversity of eelgrass now and in the past. Research can decrease epistemic uncertainty. In section 7 we include rough estimates of epistemic uncertainty along with our ratings of stressor characteristics.

Natural variability encompasses environmental characteristics that change more or less unpredictably, with weather-related variables being an obvious example. Research and monitoring can improve the understanding of natural variability, but cannot reduce it. For example, historical weather data suggest the range of conditions expected for a particular time of year or the frequency of storms, but prediction abilities are very limited and the weather itself cannot be managed to reduce variability. Natural variability can increase the difficulty of stressor research, as distinguishing the impacts of stressors from changes in eelgrass due to natural causes is challenging. In section 6 we demonstrate an approach to analyzing natural variability with the goal of detecting additional stress on eelgrass beds.

A related source of uncertainty is future sociopolitical events, such as land-use change or new regulations (or the lack thereof) for water quality or other factors affecting eelgrass. We may be able to estimate the bounds of human behavior, but we cannot fully anticipate future actions or regulatory changes.

3.0 Global and Regional Stressor Approaches

In recent years, multiple reports have documented regional and worldwide seagrass decline and discussed possible causes. In each publication, terminology differs slightly, as do the focus and detail applied to specific stressors. In Table 3.1, we summarize the stressors identified in these large-scale studies. We show where analysis of stressors in Puget Sound by Mumford (2007) and our present analysis of stressors either align with or add to those from the global studies.

The papers on global stressors surveyed here do not use systematic approaches to the ranking of stressors, although each highlights a subset of its overall list as being of high importance. Short and Wyllie-Echeverria (1996) identify water quality as the primary cause of several large-scale historical seagrass losses, and land-use change in general as the greatest threat. Short and Neckles (1999) focus on climate change, and particularly note sea level and temperature rises, changes in circulation and current energy, and salinity intrusions as key stressors. Duarte (2002) identifies increasing human populations as a driver alongside climate change, and states that the main threats from human activity on seagrasses globally are direct disruption (i.e., mechanical damage or habitat destruction) and inputs of sediment, nutrients, and sewage from land. Duarte identifies sea-level rise as the greatest future threat and a potentially important contributor to seagrass declines that have already occurred. Orth et al. (2006) state that excess nutrients and sediments have caused more significant eelgrass declines than other stressors. They also identify stressors related to climate change as key, and invasive species as a significant emerging threat. Waycott et al. (2009) suggest that key management approaches to address seagrass decline include controlling nutrient and sediment inputs and avoiding mechanical damage from boating and fishing activities.

Table 3.1. Stressors to Seagrasses Identified in Each Report. Orth's (2006) work only reflects the stressors to temperate species. The final column contains the stressors defined in this report.

Gulf of Mexico Regional Collaborative	Orth 2006 Temperate Species	Short & Wyllie-Echeverria 1996	Waycott et al. 2009	Short & Neckles 1999	Duarte 2002	Puget Sound (Mumford 2007)	This Report
BIOLOGICAL							
Algae	Eutrophication	Eutrophication			Eutrophication; Overgrowth	Competition with ulvoids and epiphytes	Nutrient-driven harmful algal blooms
Bioturbation	Bioturbation		Biological disturbance				Bioturbation
Disease	Wasting disease	Wasting disease	Wasting disease		Wasting disease		Disease
Herbivory	Herbivory	Grazing	Biological disturbance		Grazing		Herbivory
Invasive species	Introduced species		Invasive species		Invasive species	Invasive species	Invasive species
Overfishing			Overfishing			Change of trophic structure due to harvest of competitors or predators of herbivores	Overfishing
CHEMICAL							
Contaminants		Pollution			Pollution	Heavy metal toxicity	Anthropogenic contaminants
						Sulfide toxicity	Organic matter discharge/sulfides
Nutrient discharge		Nutrient Loading, N loading	Nutrient additions			Nutrient inputs	Nutrient-driven harmful algal blooms
Large river contaminants							

Table 3.1. (contd)

Gulf of Mexico Regional Collaborative	Orth 2006 Temperate Species	Short & Wyllie-Echeverria 1996	Waycott et al. 2009	Short & Neckles 1999	Duarte 2002	Puget Sound (Mumford 2007)	This Report
CHEMICAL							
Large river nutrient discharge							
			Declining water quality				
CLIMATIC & GEOLOGIC EVENTS							
			Global climate change	Climate change: CO_2, UV radiation			
Flooding							
Sea-level rise	Sea-level rise			Sea-level rise	Sea-level rise		Sea-level rise
Storm events			Storm damage, cyclone, tsunami		Increased wave action and storms		Storms
	High temperature, heat waves			Temperature	Seawater temperature rise		Sea temperature rise
	Ice scour						
		Earthquake					
PHYSICAL							
Aquaculture		Mariculture	Aquaculture		Aquaculture; clam digging, push nets	On-ground oyster culture	Aquaculture
Dredging	Dredging	Dredging	Dredging		Dredging		Dredging
Filling		Filling			Landfill		Filling
Large river freshwater volume	Hydrological					Hydrology	Freshwater input
Harvest							
Impervious surfaces							
Marinas					Ports		
Overwater structures						Overwater structures	Overwater structures

Table 3.1. (contd)

Gulf of Mexico Regional Collaborative	Orth 2006 Temperate Species	Short & Wyllie-Echeverria 1996	Waycott et al. 2009	Short & Neckles 1999	Duarte 2002	Puget Sound (Mumford 2007)	This Report
			PHYSICAL				
Large river sediment	Sediment deposition	Water Quality	Sediment Runoff		Siltation		Suspended sediment
Shoreline armoring						Armoring	Shoreline armoring
Subsidence		Earthquake					
Thermal pollution							
Vessel activity (scouring)		Boating activities	Boat propellers		Ship traffic	Boat disturbance	Propeller wash/boat wake
Vessel activity (anchoring)		Boating activities			Anchoring damage	Boat disturbance	Boat grounding/ anchor
Vessel activity (grounding)		Boating activities			Recreational boat activity	Boat disturbance	Boat grounding/ anchor
Vessel activity (wakes)		Boating activities			Ship traffic	Boat disturbance	Propeller wash/ boat wake
Water diversion	Hydrological		Coastal construction			Hydrology	Freshwater input
					Groins		
			LAND USE				
Timber							
Agriculture							
Urbanization		Construction	Coastal development		Shoreline development and infrastructure; coastal engineering		Shoreline armoring, construction, overwater structures
	Dune migration - temperate, not *Zostera marina*						

4.0 Case Studies

Key sources of information about stressors available for Puget Sound are studies conducted at specific sites, often as part of mitigation or restoration projects in eelgrass beds affected by disturbances such as construction. While these studies can be very limited in spatial and temporal scale and research scope, they are a useful source for evidence about effects of stressors on individual eelgrass beds.

We reviewed approximately 60 documents of various types that covered 23 sites within Puget Sound and one outside (Grays Harbor) (Figure 4.1). Materials included peer-reviewed articles, project reports, and less formal reports, studies, and communications. We looked for case studies where a pattern of stressors and resulting impacts was specifically observed, either temporally (before and after a stressor was add or removed from the area) or spatially (e.g., affected site and control site).

We identified 14 studies with sufficient information to include in Table 4.1. For these studies we report the spatial and temporal pattern in eelgrass distribution or density, the scale of the study and the impact if available, the controlling factor affected by the stressor and the type of evidence for the stressor. Stressors were labeled in three categories: 1) *direct* if the stressor was studied sufficiently to establish a direct link; 2) *ambiguous* for cases when the stressor was directly observed but the impact was not clear; and 3) *speculated* if the stressor was hypothesized as a likely cause of patterns seen but was not directly studied.

Many sites were studied as part of mitigation projects including the monitoring of transplants. As such, stressors identified tend to be local and specific, with a strong focus on overwater structures, boat activity, and direct alteration of substrate. Studies generally did not measure potential stressors beyond those directly related to mitigation purposes (e.g., shading from overwater structures) or easily detected during monitoring programs (e.g., algal mats). In addition, while some studies did use control plots, most projects were not fully designed as experiments. Therefore, while many of the case studies provide direct links between stressors and eelgrass, we advise caution when generalizing these results. In particular, stressors with broader, more gradual, or sublethal impacts upon eelgrass (e.g., stressors driven by climate change) are likely to be underrepresented in these studies.

The stressors that emerge from the case studies with the greatest amount of evidence for impact on eelgrass are those that directly affect substrate, along with shading from overwater structures and competition with macroalgae. Placement of shell or gravel on eelgrass habitat or disruption of habitat through digging or placing materials into the substrate effectively exclude eelgrass over time and prevent recruitment. In most cases these impacts are limited in spatial scale, but recovery of eelgrass appears unlikely without remediation of the substrate. Overwater structures and macroalgal blooms both act through reducing light availability below the requirements of eelgrass. In multiple cases, macroalgae prevented successful recruitment or transplantation of eelgrass following the removal of other stressors. Healthy eelgrass beds that have not been disrupted are less likely to be affected by macroalgal blooms, but the loss of eelgrass provides greater opportunity for macroalgae to occupy areas and hinder eelgrass return.

Another conclusion from the eelgrass study is that while most studies focused on one or few individual stressors, multiple interacting stressors were usually observed. For example, overwater structures are accompanied by boat traffic, maintenance activity, and biotic communities that would not be present without pilings. Armoring leads to changes in wave energy and substrate, as well as ongoing disruptive activities associated with maintaining beaches and armoring structures. Macroalgae, as discussed in the previous paragraph, compounds the impact of other stressors. Stressors rarely occur in isolation, making the impact of individual stressors difficult, if not impossible, to distinguish in field observations. While the effects of some stressors are straightforward, the dynamics of eelgrass at a particular site will likely be far more complex.

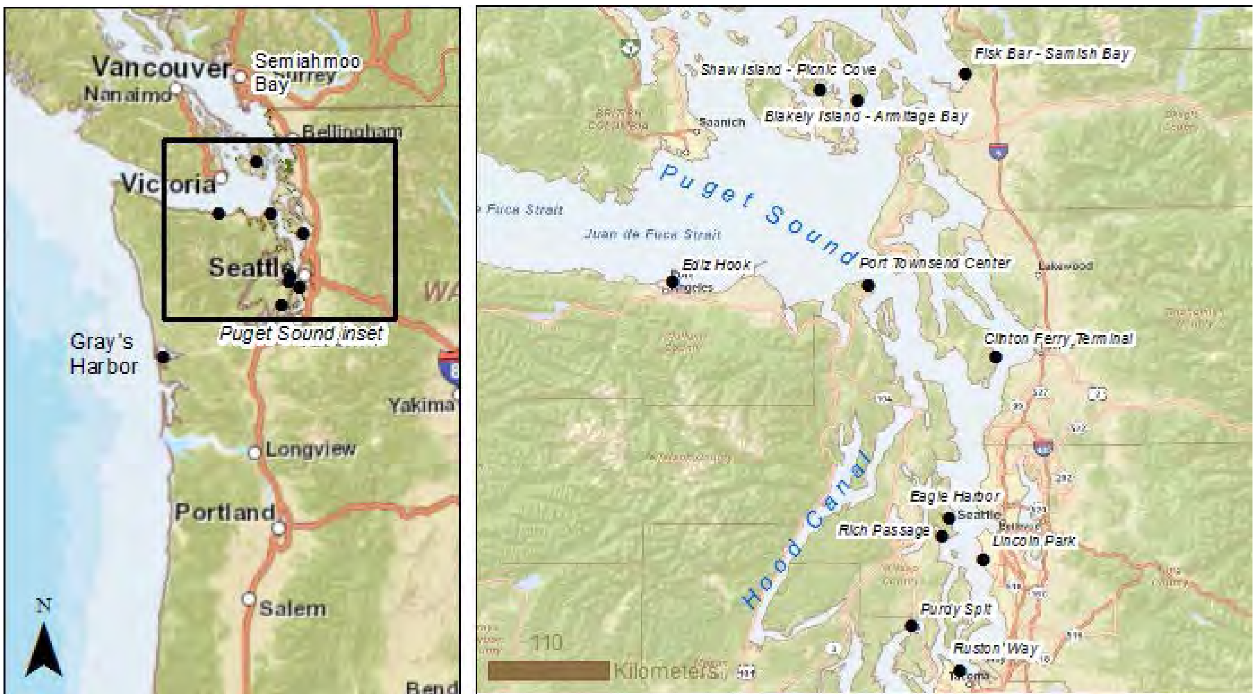


Figure 4.1. Locations of Case Studies

Table 4.1. Case Studies

Site	Reference	Time	Spatial/ Temporal Pattern	Scale of Study/ of Impact	Controlling Factor	Specific Stressor	Evidence for Impact of Stressor
Rich Passage	Woodruff et al. 2001	2000, compared to late 70's	44% decline in eelgrass since 1970	7814 m of coast had eelgrass in 1979, 4395 m in 2000	Energy	Boat wake	Ambiguous
Grays Harbor	Thom 1995	1990-1995	Eelgrass absent in shell areas; some transplant success	Transplant plots < 40 m^2	Substrate	Shell placement for nursery habitat	Direct
Purdy Spit/ Burley	Thom et al. 2008b	2003-2007	Loss of eelgrass at aquaculture site	58.5 ha study area; 595 m^2 lost to aquaculture	Substrate	Plastic tubes for geoduck aquaculture	Direct
					Light	Shading from nets and fouling of nets	Speculated
Eagle Harbor	Thom et al. 2001c	1998-2000	Transplanted eelgrass failed; reference site healthy	0.6 acre (2428 m^2) transplant site	Competition	Drift macroalgae	Direct
				Reference site along 100 m baseline	Substrate	Bioturbation (crab)	Direct
					Substrate	Boat anchoring/ grounding	Direct
Picnic Cove, Shaw Island	Austin et al. 2004	1993-2001	Linear scar in bed; recovered after remediation and transplants	3.9 ha meadow, 0.09 ha impact	Substrate	Mechanical disturbance and anoxic sediment from cable placement	Direct
Port Townsend NW Maritime Center	Diefenderfer et al. 2005	2004	Partial success of transplants after dock relocation	510 m^2 study area; 228 m^2 transplant area	Light	Overwater structure	Direct
					Competition	Macroalgae	Direct
Clinton Ferry Terminal	Thom et al. 1997	1994	Absence of eelgrass within 5 m of dock and prop flume	Study area 500 m to each side of terminal; expansion expected to directly impact 320 m^2	Light	Overwater structure	Direct
					Light; substrate	Propeller wash; maintenance activities	Direct
					Substrate	Bioturbation; disturbance from seastars	Speculated
Lincoln Park	Antrim et al. 1993	1988-1993	Narrow distribution, inter-annual variability	About 600 m^2 of eelgrass observed in 1993, roughly 1 km of coastline	Substrate	Lack of sandy substrate (unclear if fill responsible)	Ambiguous
					Energy	Wave energy	Speculated

Table 4.1. (contd)

Site	Reference	Time	Spatial/ Temporal Pattern	Scale of Study/ of Impact	Controlling Factor	Specific Stressor	Evidence for Impact of Stressor
Ediz Hook	Pentec Environmental 2001	1998-2001	40% initial survival of transplants, then healthy	Mitigate for 430 ft^2 (40 m^2) loss, 1880 ft^2 (175 m^2) planted	Light	Weather/ sunlight	Speculated
Semiahmoo Bay	Thom et al. 1994	Study in 1991; gravel present > 5 yrs	Eelgrass present on sandy substrate, absent on graveled	1.5 ha graveled plot	Substrate	Graveling	Direct
Ruston Way/ Commencement Bay	Elliott et al. 2006	~2005	Subtidal eelgrass reduced and intertidal absent near old mill sites	7 sites along ~4 km coastline	Substrate/ contaminants	Wood waste increasing hydrogen sulfide	Direct
Armitage Bay, Blakely Island	Nelson and Lee 2001	1999-2000	Highest eelgrass density where algae naturally absent; higher density on edge where algae removed	m^2 study plots, bed size not specified	Light, competition	Ulvoid algae	Direct
Hood Canal	Simenstad 2008	2000	More eelgrass on less-armored sections of heavily armored areas; no pattern elsewhere	Hood Canal and eastern Strait, 4 ha sampling blocks	Energy, substrate?	Shoreline armoring	Ambiguous
Fisk Bar, Samish Bay	University of Washington 2011	2007-2010	Decreased density, flowering, size, and belowground branching after geoduck harvest	145x40 m farm adjacent to larger meadow	Substrate, light	Geoduck aquaculture	Direct

5.0 Spatial Quantification of Stressors

The purpose of this section is to provide a baseline understanding of broad landscape trends for the current distribution of stressors within Puget Sound and across each of the Submerged Vegetation Monitoring Project (SVMP) sampling regions. This provides a summary using the same unit of analysis as used by the DNR in their monitoring.

The impact of stressors on eelgrass can be described as a function of the magnitude, extent, and duration of the stressor as well as the condition of the eelgrass bed itself. To assess impact, understanding of both the location and extent of the stressor and eelgrass meadows is needed as well as understanding of the mechanism of impact. However, for both historical and present-day conditions, limited spatial information is available about where stressors are and the location/extent of eelgrass meadows.

To gain a better understanding of the potential types of stressors acting historically and in the present, we summarized high level categories of stressors over Puget Sound and within each of the eelgrass survey regions in Puget Sound based primarily on existing GIS datasets. High level categories include population growth and coastal and watershed development, which lead to many of the stressors identified in the conceptual model. In addition to the indicators for each category, limited present day coastal stressors (overwater structures, shoreline armoring and 303(d) and 305(b) contaminated sediments) have been summarized.

5.1 Assessment Regions

Seven assessment regions were identified by DNR based on the SVMP sampling regions: San Juan (sjs), Straits (str), Hood Canal (hdc), North Puget Sound (nps), Saratoga-Whidbey (swh), Central Puget Sound (cps), and South Puget Sound (sps) (Figure 5.1). Level 10 Hydrologic Units (HUCs) were aggregated to represent the land-based watershed for each region of interest (Figure 5.1). There were some slight differences between boundaries of assessment regions and watershed units, and one coastal HUC, located in Central Puget Sound and Saratoga-Whidbey sampling regions, transcended boundaries between assessment regions. These regions are used in this spatial quantification for broad scale stressor reporting. In addition, the base eelgrass sampling frame created by the DNR based on depth to identify sites and extents for eelgrass monitoring (Berry et al. 2003) was used to identify impaired waters and sediments within the vicinity of eelgrass habitats and to examine the intensity of overwater structures within potential eelgrass habitat. For the purpose of this report, individual units within the sampling frame will be referred to as *sampling frame sites*.

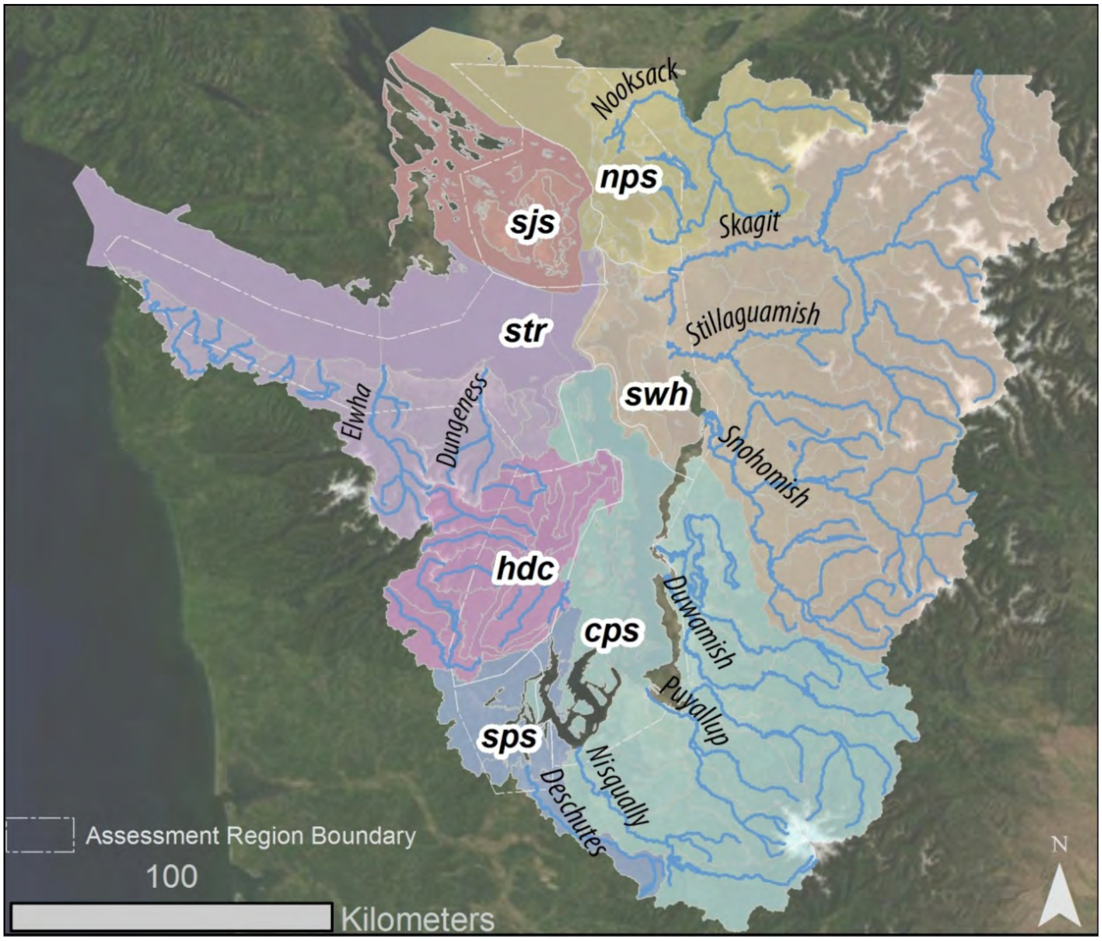


Figure 5.1. Assessment Regions Based on SVMP Sampling Areas and Adjoining Watersheds: San Juan (sjs), Straits (str), Hood Canal (hdc), North Puget Sound (nps), Saratoga-Whidbey (swh), Central Puget Sound (cps), and South Puget Sound (sps)

O'Sullivan and Unwin (2003) described issues with spatially aggregating data collected on a more detailed resolution, using the term *modifiable areal unit problem* to refer to the issue of aggregating at a unit that is not driven by the features of interest. Accordingly, different aggregation units can yield very different results. For example, the occurrence of an overwater structure is not driven by the SVMP sampling regions, nor do impacts act on the SVMP sampling region level. Changing the unit boundaries would likely change the apparent level of stress that eelgrass meadows within units are experiencing. The same is true for eelgrass meadows themselves. Though sites within the sampling frames are surveyed as distinct meadows, ecologically, they may be connected. It should be noted that spatial variation and the impact of stressors on eelgrass likely occurs at a more local scale than that at which the datasets are reported and aggregated. In addition, eelgrass meadows near the border of adjoining assessment units likely are impacted by stressors in other units.

5.2 Indicators of High-Level Stressors

Indicators that represent or are correlated with high-level stressors are identified in Table 5.1. These indicators were either mapped or the presence/abundance was calculated across assessment units.

Table 5.1. High-Level Stressors and the Datasets and Sources That Represent Them. The columns labeled *visual* and *quantified* show whether the dataset is mapped or summary statistics are calculated across the region. The final column provides the cross-link to elements in the conceptual model.

	Stressor or Indicator	Visual	Quantified (Method/Unit)	Data Source	Conceptual Model
Watershed Development	1880s, Navigation Charts Railroads Roads Diked areas Logged areas Log/quarry equipment Ferries	X		T-sheets; Digitized by Puget Sound River History Project. http://riverhistory.ess.washington.edu/ ; Compiled by PSNERP.	Direct Link to Stressors: Suspended sediment Freshwater input Nutrient-driven harmful algal blooms
	1930s Forest Cover	X		ArcGIS online. Pacific Northwest Experimental Station, US Forest Service.	
	1980 (approx) land use/land cover	X	% Impervious, HUC[(a)]	1:250,000 Scale Quadrangles of Land use/Land cover GIRAS[(b)] Spatial Data in the Conterminous United States http://water.epa.gov/scitech/datait/ models/basins/metadata_giras.cfm	
	1992 land use/land cover	X	% Impervious, HUC	1992 National Land Cover Dataset; USGS[(c)]	
	2001 land use/land cover; Impervious Surface	X	% Impervious, HUC	2001 National Land Cover Dataset; USGS	
	2010 Land Cover	X		2010 Washington State Land Use; Washington Department of Ecology. http://www.ecy.wa.gov/services/gis/data/landuse/landuse.htm	
Coastal Development	Shoreline change to artificial: 1880s to present day	X	By SVMP	Historical: T-sheets. Digitized by Puget Sound River History Project. http://riverhistory.ess.washington.edu/ ; Compiled by PSNERP. Present: PSNERP shoreline	Direct Link to Stressors: Dredging/Filling Shoreline armoring

Table 5.1. (contd)

	Stressor or Indicator	Visual	Quantified (Method/Unit)	Data Source	Conceptual Model
Coastal Stressors of Interest	Overwater structures	X	By SVMP	PSNERP	Overwater structures
	Shoreline Armoring	X	By SVMP	PSNERP; Compilation of County Datasets	Shoreline armoring
	303(d)/305(b) sites	X	By SVMP, identify within current survey area, or 300 ft (91 m) from historical bed	Washington Department of Ecology http://www.ecy.wa.gov/services/gis/data/data.htm	Anthropogenic contaminants
Population Growth	Counties in Puget Sound Metropolitan areas	X	By County, Urban Growth Areas in SVMP watersheds	http://www.ofm.wa.gov/pop/decseries/historicalpop.xls	Direct Link to Stressors: Overwater structures, Construction, Boat grounding/anchoring, Propeller wash/boat wake, others

(a). Percent impervious calculation comparison between years was dropped after review of results. See "Water Impervious Surface and Land Use" section.
(b). Geographic Information Retrieval and Analysis System
(c). United States Geological Survey

5.3 Overview of Regional Findings

Over the past century the location and the intensity of development related pressures have shifted. Logging and agricultural activities and landscape modifications associated with development and pursuit of these activites during the first half of the twentieth century were likely major regional stressors for eelgrass meadows. This includes direct disturbance, such as a variety of filling, armoring, and industrial activities that likely had strong local, direct effects in specific sites. Population growth in rural and urban expansion and associated activities during the second half of the twentieth century likely continue to be major stressors for eelgrass meadows.

However, these stressors are not equally distributed over Puget Sound or on its eelgrass meadows. Moran's I, a measure of spatial autocorrelation, indicates that direct stressors of overwater structures and shoreline armoring are not randomly distributed throughout the Sound ($p < 0.001$), and do exhibit a significant level of spatial clustering when evaluated per eelgrass survey unit. It should be noted that Euclidean distance was used to assess clustering throughout the study area; in a marine setting, calculations of distance should consider the topography of the study area (functional distance). However, this does support what is evident when looking at a map of Puget Sound: many stressors are more likely to be found in populated areas and thus tend to be clustered together. It is likely that eelgrass beds located near these expanding population centers have had multiple and changing stressors throughout the past century. However, as for attributing the source of loss for individual eelgrass meadow, further knowledge of local conditions and stressors at the time of loss is needed. Table 5.2 provides a regional summary and comparison of these stressors.

Not much has been written about the importance of landforms for assessing relative differences of the impacts of stressors on seagrasses. However, it is probable that inlets and bays within the region where there is a greater land surface area to water ratio will be more directly affected by local watershed management than open, coastal regions, and likewise, river deltas and surrounding areas will be more heavily influenced by upper watershed management. For this reason, land use management and development in the Hood Canal, South Puget Sound and Central Puget Sound regions may be extremely critical in maintaining and recovering eelgrass populations in those areas.

Table 5.2. Regional Results of High-Level Stressor Analysis

Region	Population	Coastal Development	Watershed Development
All of Puget Sound	Population today is 8 times the population at turn of the century. Growth has not been equally distributed throughout the Sound, and the growth rate was highest during the second half of the century.	Direct disturbance of the shoreline has increased with dredging, filling, shoreline armoring.	Three trends throughout the Sound: 1) a development of agriculture in the first part of the twentieth century, followed by a decrease in agricultural area and conversion to residential and urban areas by the twenty-first century; 2) heavy logging activities until the 1930s and an increase in forest cover by the late 1970s; and 3) an increase in impervious surfaces since the 1930s to present day, focused on the Puget Sound lowlands.
Hood Canal	Low population growth and low population density both across counties and within urban growth areas.[(a)] Stressors related to population likely deal with dispersed distribution of services, such as septic systems, dredging and filling, and roads.	Few and dispersed artificial shoreforms. Initial construction may have had a local impact on nearby eelgrass beds. Low-moderate coverage of overwater structures, with local hotspots including military areas, probable disturbance of locally adjacent meadows. Moderate level of shoreline armoring. Moderate-high number of issues with water quality, particularly dissolved oxygen and fecal coliform; however, uncertain about impact on eelgrass beds.	Total impervious area is low, although historically, heavy logging is evident in the 1930s on the western shore. Logging likely led to locally increased sedimentation, particularly near the mouths of rivers or along shorelines adjacent to logging activity. Depending on location and intensity, this may have affected eelgrass meadows.
North Puget Sound	Low population density with low-moderate density in urban growth areas (near Bellingham Bay). Likely localized stress in and around Bellingham Bay from population growth as well as distribution of services in rural areas.	High percent of shoreline became artificial since the 1800s. Change concentrated on shorelines in and around bays (Bellingham and Samish). Probable historic impact on habitat. High level of disturbance due to armoring and overwater structures as well as high localized sediment contamination and occurrence of water quality impairment. It is likely that these stressors have directly disturbed eelgrass meadows in the past, particularly in Bellingham Bay.	By the 1800s, diking and hydrologic alterations were evident in Bellingham Bay with shipping activities near Bellingham and the Nooksack. Agricultural activities are evident along the Nooksack River by the 1930s. Today, coastal watersheds contain 5-16% total impervious area, though the unit adjoining north Bellingham Bay has over 16% total impervious area. It is likely that these activities have had an impact on aquatic habitats in and around altered areas like Bellingham Bay and issues with turbidity near the mouth of the Nooksack. Runoff from impervious surfaces may currently affect eelgrass meadows in the region.

Region	Population	Coastal Development	Watershed Development
Saratoga-Whidbey	Low population density localized high growth on Whidbey Island. Potential impacts in and around high growth area.	Moderate level of artificial shoreform, concentrated near the Snohomish and Skagit deltas with isolated areas near population centers. These modifications likely had a local impact on habitat. Low to moderate level of shoreline armoring and overwater structures relative to the rest of Puget Sound.	In the 1930s, evidence of widespread logging activities in higher reaches of the watershed. Today, there is still much agricultural land in the lowlands of this region, with moderate to high total impervious areas.
South Puget Sound	Moderate population density and growth, concentrations centered near Olympia. Probable construction and commerce related stressors on eelgrass beds have occurred near Olympia.	It is unknown if eelgrass ever inhabited South Puget Sound. It has not been found there in recent years, though historically, the conditions appear suitable. Low level of artificial shoreform, although some artificial areas evident in inlets. Moderate levels of armoring and low-moderate cover by overwater structures. No sediment contaminants in eelgrass survey areas, but multiple 303(d) water quality issues. The majority were fecal coliform although temperature and dissolved oxygen issues were evident in five or more sites. Poor water quality may have impacted eelgrass beds in region or may currently inhibit recolonization. Further information would be needed about location and health of beds as well as water quality parameters. Shoreline armoring and overwater structures likely would have a localized impact on eelgrass meadows, if present.	By the 1800s, Olympia had begun developing and logging was occurring on the adjacent Eld Inlet. In the 1930s, agricultural lands surrounded Olympia and much of the watershed showed evidence of recent timber harvest. Olympia has remained an urban development region, with total impervious area between 8-16%. Adjoining subwatersheds within the region have lower total impervious areas.
Central Puget Sound	High population density with high growth. Likely multiple construction and activity related stressors on eelgrass beds near populated areas.	High level of artificial shoreform with concentration in and around Seattle. Likely impacts on eelgrass beds. High level of shoreline armoring and overwater structures. It is probable that eelgrass meadows experience both local, direct stressors as well as disturbance of the natural habitat forming processes.	High level of watershed development. Likely increases in nutrient inputs, algal blooms, higher turbidity, increased sedimentation.

Region	Population	Coastal Development	Watershed Development
San Juan	Low population growth and density.	Lowest amount of artificial shoreform. Initial construction may have had a local impact on adjacent eelgrass beds. Low quantities of overwater structures and shoreline armoring, although inlets and bays have higher concentrations. Temperature, fecal coliform, and dissolved oxygen are water quality issues within water bodies near eelgrass survey areas in the San Juans.	Agricultural development had occurred in the study area by the 1800s as well as shipping. By the 1930s, much of the forested area had been logged. Today, rural agriculture and forested areas cover the region and total impervious area is under 5%. Historically, both logging and agriculture likely increased nutrient inputs as well as sedimentation. Early development and industry in the area may have had an early impact on eelgrass beds.
Straits	Low population growth and density, with increased population growth in the second half of the twentieth century. Stressors relation with population likely deal with dispersed distribution of services.	Low level of artificial shoreform, although some artificial areas evident in Port Angeles, Clallam, and Neah Bays. Low, but concentrated levels of overwater structures, low 303(d) and 303(b) counts. Low-moderate levels of shoreline armoring.	Agriculture and logging activities were evident in the 1930s likely increased turbidity. Low levels of urbanization and increased forest cover characterized the second half of the twentieth century. Stressors associated with increased recreational and commercial use of nearshore may have an impact on eelgrass beds
(a). Categories of Low, Medium, and High are based on comparison between assessment regions and mean for Puget Sound. In general, the two highest and lowest regions are termed “high” and “low” in this table. Exceptions were in case of natural breaks within the data. For example, there are three regions in Puget Sound with counties with much lower population growth and density than other regions: Hood Canal, Straits, and San Juans. All three are described as having low population growth and density, rather than just the bottom two.			

5.4 Population Density and Growth

Twelve counties lie within the Puget Sound watershed[1]: Clallam, Jefferson, Mason, Thurston, Pierce, Kitsap, Island, San Juan, King, Snohomish, Skagit and Whatcom. While some counties, like Jefferson and Clallam also extend outside the watershed, the major centers of population are within the watershed. Over the past century, these areas have seen a total growth from under 500,000 to nearly 4 million people (Figure 5.2). Growth, and thus distribution of stressors, has not been equally distributed throughout the Sound. Today, King, Pierce, and Kitsap counties have greatest population densities (Figure 5.3), each directly contributing to the Central Puget Sound assessment region. Snohomish and Thurston counties, contributing to the Saratoga-Whidbey and South Puget Sound assessment regions respectively have the next largest densities. Population centers in these counties are located along the coast.

[1] The definition of Puget Sound and its extent has differed over the years and between agencies. For the purpose of this report, the Puget Sound watershed refers to U.S. areas that directly contribute to the SVMP sampling areas.

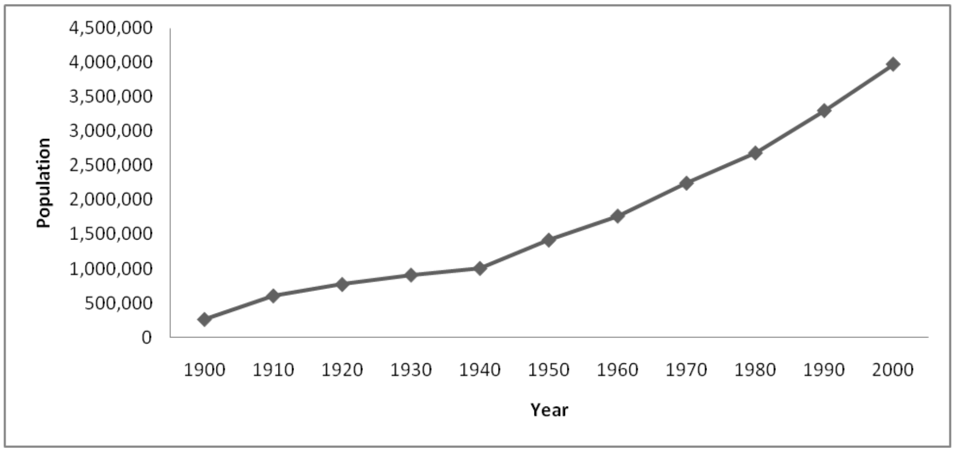
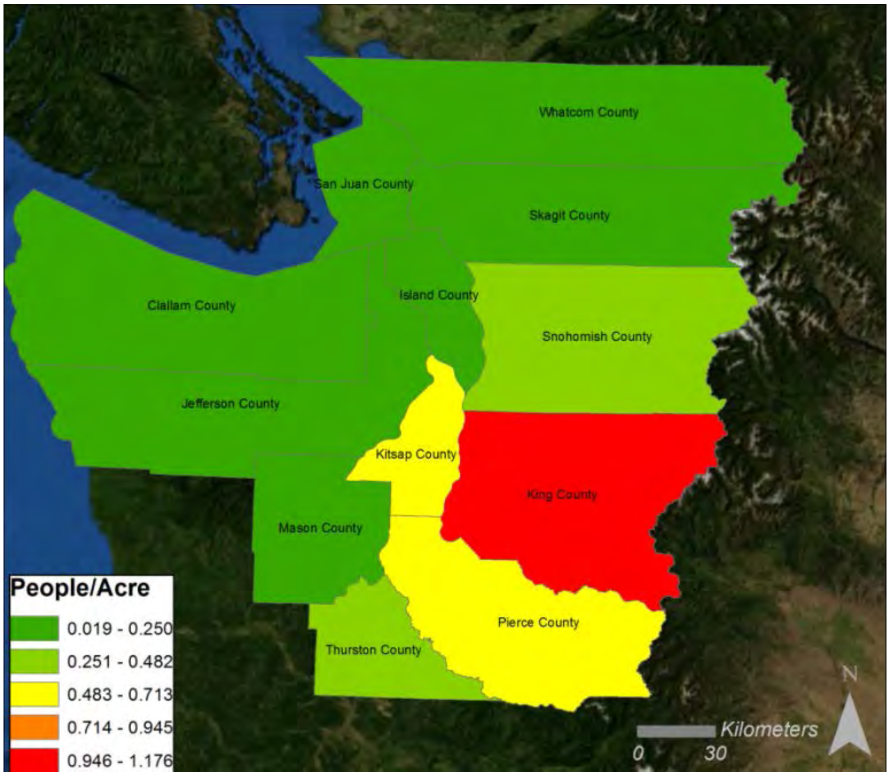


Figure 5.2. Population Growth 1900 -2000, Counties in Puget Sound Watershed. The slope of the line indicates the rate of growth. Population growth rate was higher in the second half of the century (1950–2000) than in the first (1900–1950).

While population density is directly related to various activities that may stress eelgrass, population growth rates can indicate direct activities related with infrastructure development such as dredging and filling. The rate of population growth increased in the second half of the century, with increased development and population density in urban growth areas (see Appendix B). Among the eelgrass sampling areas, population density accelerated most rapidly in King County within the Central Puget Sound monitoring area, and countywide, King County contains the highest density of people per acre of land. Kitsap and Pierce counties have the next highest densities. In the last 50 years, the greatest increases in population density were seen in King, Kitsap, Pierce, Thurston, Island, Pierce, and Snohomish counties. It is likely that stressors associated with population growth and infrastructure development such as overwater structures, armoring, digging, filling, and vessel activity have had strong impacts on eelgrass meadows within the Central Puget Sound and Saratogy-Whidbey sampling areas. Although the Southern Puget Sound sampling area currently has no known eelgrass meadows, past stressors may have made potential habitat unsuitable for eelgrass growth or establishment.

Transportation and infrastructure needed to connect populated places and move people, materials, and energy have likely impacted beds in their initial construction and maintenance. In addition, areas with less urban growth, such as Hood Canal, the Straits, and the San Juan regions, may experience more direct disturbances related to non-pooled resources (e.g., septic tanks vs sewer system).



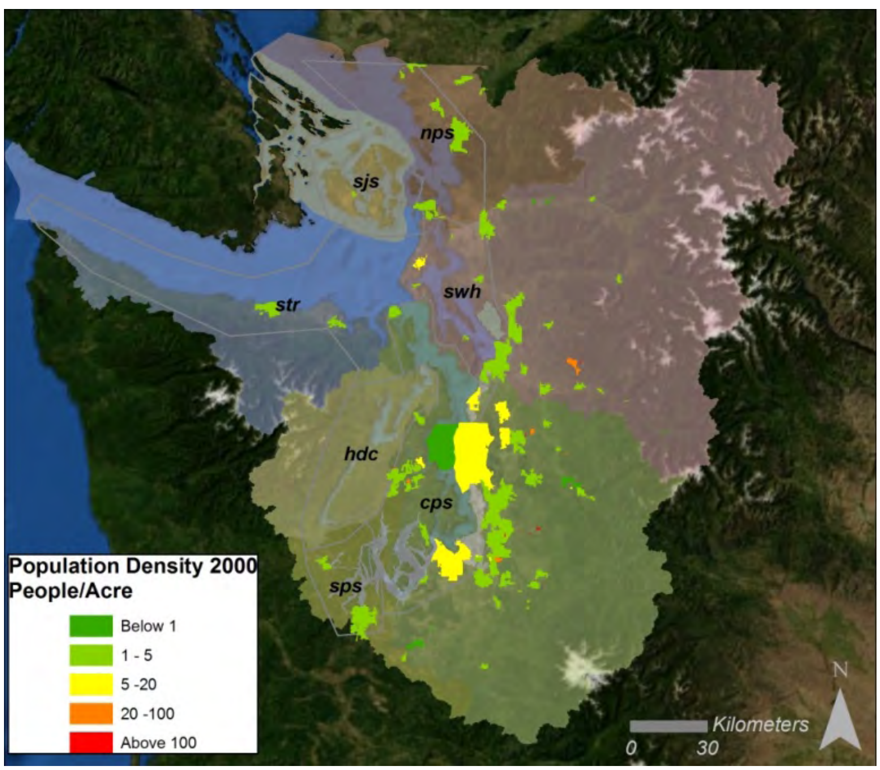


Figure 5.3. Population Density by County (Above) and by Urban Growth Areas (Below) in 2000. Areas in the Central Puget Sound sampling area have the greatest population densities, although growth areas in the South Puget Sound and Whidbey Island sampling areas also show higher densities.

5.5 Watershed Impervious Surface and Land Use

A variety of sources were used to visualize the change in land cover throughout the last century. Sound-wide, three trends are evident: 1) a development of agriculture in the first part of the twentieth century, followed by a decrease in agricultural area and conversion to residential and urban areas by the twenty-first century; 2) heavy logging activities until the 1930s and an increase in forest cover by the late 1970s; and 3) an increase in impervious surfaces since the 1930s to present day, focused on the Puget Sound lowlands.

In the 1880s, initial urban development and natural resource extraction of timber, fish, and stone were evident in Puget Sound (see Appendix B). Areas within the Strait and Central and Southern Puget Sound showed heavily logged areas. Hydrologic alterations, including extensive diking, were evident in the current North Puget Sound, Central Puget Sound, and Saratoga-Whidbey sampling areas. By the 1930s, the land cover classification shows four intensive areas of coastal agriculture in Puget Sound along the Nooksack, Deschutes, Dungeness, and Puyallup rivers. It is likely that eelgrass beds in the vicinity of these areas experienced increased siltation, reduced light, increased competition from algal blooms, and perhaps burial of some beds. It is likely that diking altered the hydrological regime in these river basins and floodplains. In certain areas, like Padilla Bay, it is hypothesized that alterations including re-routing of the Skagit River may have altered conditions to be more suitable for sustaining eelgrass growth (Dowty et al. 2010).

Urban growth increased from the 1950s to present day. Stressors related to urban growth include increased shoreline modification, likely increased wave energy, frequency of disturbance, and vessel-related activities. Forestry and related activties were evident in each of the current sampling areas.

A look-up table was initially used to classify impervious surface based on land use/land cover and report the results by HUC 10 watersheds for 1980, 1992, and 2001 datasets (Appendix B). However, different classification schemes were used between years and the 1980 classification was completed with lower resolution than the 30-m 1992 and 2001 data sets, limiting the potential for comparison between years. The difference in average percent impervious surface between years was less than 1% per hydrologic unit. Error for classification appeared to be greater than 1%, because some units stayed the same or decreased between timesteps. This did not permit an inter-annual comparison by decade. However, it should provide a metric with which to examine the spatial variability within a year between HUCs.

5.6 Coastal Development Trends

Coastal development is used here to refer to development taking place in immediate proximity to the shoreline, including nearshore construction, fill, dredging, and shoreline armoring. These stressors can directly disturb eelgrass beds through burial or uprooting and modify natural processes such as bank erosion and sediment depostion. Preliminary indicators from past studies show a 15% loss in shoreline length from the 1880s to today, indicating that the shoreline has become less complex over time with armoring and fill modifying the shoreline morphology. However the sources of data and the level of simplification in shoreline digitization differed between datasets (Anchor 2008; Puget Sound Partnership 2010).

Coastal geomorphology refers to the shape and geology of shorelines. Classifications of geomorphic types have been used to interpret ecological functions and services that certain portions of the shore provide. The Point No Point Treaty Council classified both historic shoreforms in Puget Sound from the coastal survey in the 1800s and present day. This information was re-classified in the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) dataset. A classification category of "artificial" was used to indicate portions of shorelines where the geomorphology was sufficiently altered from its natural condition to make the shoreline no longer function as it would in its natural state (see Figure 5.4).

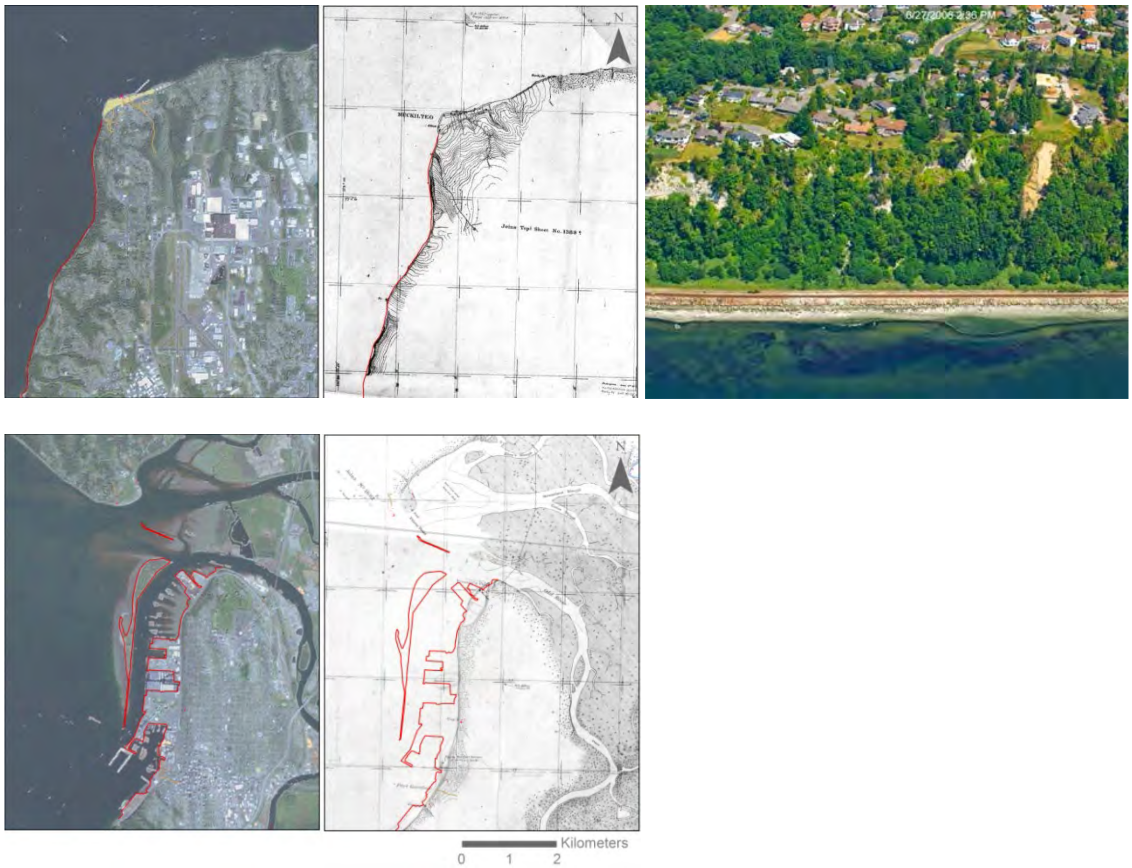


Figure 5.4. Sample Geomorphic Classification. Aerial imagery and historic T Sheet with shoreline classified as artificial in red. A railroad (oblique image above from DOE 2006) cuts former bluff off from delivering sediment to the beach, and that portion of the shoreline is classified as artificial (upper left). Other modifications such as fill (lower left) also change class.

As an indicator of direct coastal development since the 1800s, we calculated the percent change in the artificial class from historic conditions to present day, but used the modern-day shoreline to reduce error due to differences in data capture (Table 5.3). Within Puget Sound, North Puget Sound, and Central Puget Sound shorelines exhibit the greatest modifications in geomorphic type since the 1800s. However, there is much variation within the survey units (Figure 5.5). Within North Puget Sound, portions of Bellingham Bay and Padilla Bay exhibit the greatest changes.

Table 5.3. Percent Change in Artificial Shoreline by Sampling Region From Historic Conditions to Present Day

Region	Increase in Artificial Geomorphology Shoreline (%)
Hood Canal	2.66%
North Puget Sound	19.16%
Saratoga-Whidbey	9.13%
South Puget Sound	4.84%
Central Puget Sound	16.18%
San Juan Islands	0.97%
Straits	4.93%
Puget Sound Total	9.37%

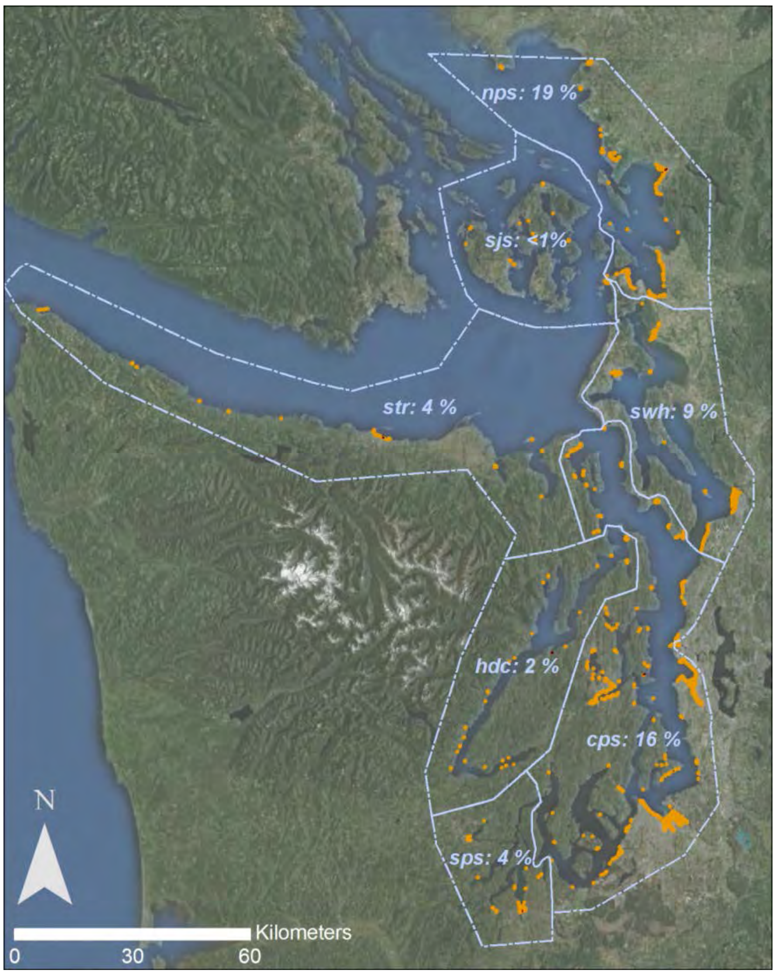


Figure 5.5. Geomorphic Change by Assessment Region. The percent shown in the figure refers to the percent of shoreline in each region that converted to an *artificial* geomorphic classification since the 1800s. Shorelines highlighted in orange illustrate where these changes took place.

5.6.1 Coastal Stressors of Interest

Using the compiled PSNERP database for Puget Sound, we calculated the coverage of overwater structures and shoreline armoring relative to the shoreline length in each unit (Table 5.4). In addition, we reviewed 303(d) and 305(b) sites within potential eelgrass sampling areas.

5.6.1.1 Known Limitations

In a prior study in Kitsap County, we compared the PSNERP-identified overwater structures to the number of overwater structures identified in Kitsap County's Shoreline Survey gathered by a global positioning system in the field. We found an approximate 20% difference in the overall number of structures identified in the two studies, with the vast majority of differences due to smaller floating structures without pilings being identified in the ground survey but not in the aerial image classification. The projected average size of the missing structures was under 100 ft^2. It is likely that the resolution in the aerial imagery was not sufficient to capture these smaller structures. Similar differences are likely found within aerial classifications of other small or vertically oriented features (see Anderson et al. 2011).

5.6.1.2 Armoring

According to the dataset, approximately 27% of Puget Sound's nearly 13 million feet of shoreline is armored. However, this varies across the Sound. In Central Puget Sound, over 45% of the shoreline is currently armored, whereas in the San Juan region, only 5% of the shore is armored.

5.6.1.3 Overwater Structures

Across Puget Sound, there is an average of 4 ft^2 of overwater structure per linear foot of shoreline, with over 1,400 acres of overwater structures. Central Puget Sound contains the largest area covered by overwater structures and the greatest ratio of overwater structure to linear feet shoreline present. The San Juan region has the lowest density of overwater structures.

As only some portion of overwater structures overlie eelgrass habitat, the area of eelgrass habitat affected by shading will be less than the estimated total area of overwater structures. A separate assessment, focusing on overwater structures within the estimated depth range of eelgrass found approximately 412 acres of overwater structures within the correct depth band for eelgrass (Dowty pers. comm.). However, the identified range based on field data capture, when applied to a different scaled spatial data set, did not capture one-third of the surveyed points where eelgrass was present at a test region in Hood Canal. Consequently, selected areas of overwater structures were also limited, thereby underestimating the impact. However, these two assessments do provide bounds for the impact of overwater structures on the light regime. Dowty further refines this estimate by assuming the impact of shading affects three times the area of the structure. Only 40% of the resulting area would have eelgrass and thus be affected.

Looking at where these structures fall within the Sound also provides clues to their impact. Fragmentation of habitats has been linked to impacts on species within these landscapes as well as the sustainability and self-maintenance of the habitat. While studies have shown little conclusive evidence of the impact of seagrass fragmentation on species that they support (Boström et al. 2011), the small patches that result from fragmentation tend to be less stable than larger beds and more susceptible to storm events, while gaps between patches may serve as opportunities for competitors (Fonseca and Bell 1998; Duarte et al. 2006; Bell et al. 2006).

The importance of fragmentation to the persistence of eelgrass beds over time is not well understood. Fonseca and Bell (1998) identified a 59% cover threshold within a study area as the difference between a continuous eelgrass meadow and patchy beds that are more susceptible to wave energies. Within forested landscapes, fragmentation has been described as 10 to 60% habitat loss (McIntyre and Hobbs 1999). Dowty (pers. communication) estimated current eelgrass habitat within Puget Sound as averaging 40% cover over Puget Sound within the correct depth range for eelgrass growth, yet this cover varies within sites. Current DNR efforts include refining the estimate to eliminate areas that are not eelgrass habitat. Nonetheless, when interpreting the potential impact of overwater structures and other direct impacts to eelgrass in Puget Sound it is important to look at the consequences of fragmentation. For example, overwater structures are highly spatially clustered, although they have less than a 1% cover in Puget Sound sampling frame sites, approximately 12% of sampling frames with overwater structures have a >5% cover. Depending on the current eelgrass cover in the area and the footprint of impact beyond the overwater structure, areas may be less resilient to future changes and additional stresses. With increasing occurrence of direct stressors, further research is needed to understand the impact of fragmentation caused by direct disturbance on the resilience of eelgrass meadows.

5.6.1.4 Potential Future Trends

According the WDFW Hydraulic Project Approval database, approximately 1 mile of new armoring is constructed across the Sound per year (Carman 2010). However, these rates may change in the future. Changes in attitudes with perceived or actual risks due to climate change may alter the rate of armoring and increased population concentrations may alter the size of new overwater structures built to support more than one household.

Table 5.4. Stressors of Interest by Region and for Puget Sound

Region	Shoreline Length (miles)	Sites in Sampling Frame for Eelgrass Survey (sq miles)	Overwater Structure Area (acres)	Overwater Structure Density (acres/ shoreline mile)	Percent Shoreline Armored	305(b) Sediment Contaminant Occurrences in Eelgrass Survey areas[a] [b]	303(d) Water Quality Occurrences [a] [c]
Hood Canal	245	28	63	0.258	21.29%	0.14	2.34
North Puget Sound	250	98	184	0.736	31.71%	3.08	0.74
Saratoga-Whidbey	343	100	144	0.419	21.67%	0.21	0.30
South Puget Sound	206	25	66	0.322	26.96%	0.00	2.56
Central Puget Sound	734	81	803	1.095	47.61%	1.00	2.3
San Juan	454	33	90	0.199	4.29%	0.42	0.85
Straits	220	46	47	0.215	15.38%	0.00	0.61
Puget Sound	2,451	410	1,398	0.571	27.09%	1.04	1.09

(a). One site may have multiple contaminant issues.
(b). Count, class 2, 4, or 5 per square mile of eelgrass survey area.
(c). Count, class 5 per square mile of eelgrass survey area.

5.6.1.5 Water Quality

The impact of anthropogenic chemicals on seagrasses is not well studied. In a review of toxicity on seagrasses, Runcie et al. (2005) cite studies that link ammonium toxicity to seagrass decline, connect increased run-off to increased sulfide levels from organic matter, measure impacts from heavy metals and herbicides, and examine the decrease in resilience of seagrass to other stressors after exposure to petrochemicals. Ralph et al. (2006) points out that the timing of exposure to toxicants is important as well, with different outcomes depending on the stage of development of seagrasses.

The 1972 Clean Water Act requires states to provide biennial reports on water bodies under their jurisdiction. Section 305(b) requires reports of water body conditions; a subset of those, the 303(d) list are an inventory of impaired waters. Within Washington State's 305(b) water body classification, the following categories are used to represent different levels of impairment (WADOE 2011):

- Category 1: Meets standards for clean water
- Category 2: Waters of Concern – some evidence of a water quality problem
- Category 3: Insufficient data
- Category 4: Polluted waters that do not require a total maximum daily load (TMDL)
- Category 5: Water bodies than are impaired and need a TMDL

To gain a better understanding of occurrence relative to nearshore areas, the WADOE GIS datasets were assessed to identify contaminated waters and sediments within 300 ft of current sampling frames.

Water Quality

In current sampling frame sites, there are over 300 occurrences of category 5 water quality impairment. The Central Puget Sound sampling area has the most documented occurrences. However, for the relative area of water, the documented occurrences in the South Puget Sound and Hood Canal sampling area are both high. According to the analysis of 303(d) and 305 (b) data, in all SVMP regions, fecal coliform and dissolved oxygen are the most common documented water quality issue in eelgrass sampling areas. Fecal coliform is the most common, with the exception of Hood Canal where dissolved oxygen has a high occurrence (Table 5.5). In the San Juan sampling areas, temperature also has been documented as being impaired at five sites.

Sediment Contamination

In the current survey areas that have eelgrass, 46 sites have known or suspected marine sediment contamination. Two sites, Liberty Bay and Bellingham Bay, have over 40 different contaminants. Within historic eelgrass beds, 55 sites have known or suspected sediment contamination, including 515 occurrences of sediment contamination within 300 ft of a bed.

Table 5.5. 303(d) Occurrences Within Eelgrass Beds in Puget Sound by Region. A site may have multiple water quality issues.

Region	Parameter	Count	Percent
cps	Copper	3	2%
	Dissolved oxygen	67	36%
	Fecal coliform	107	57%
	pH	7	4%
	Temperature	3	2%
hdc	Dissolved oxygen	32	49%
	Fecal coliform	28	43%
	pH	1	2%
	Temperature	4	6%
nps	Dissolved oxygen	19	26%
	Fecal coliform	43	60%
	pH	9	13%
	Temperature	1	1%
sjs	Dissolved oxygen	8	29%
	Fecal coliform	15	54%
	Temperature	5	18%
sps	Dissolved oxygen	15	23%
	Fecal coliform	41	64%
	pH	2	3%
	Temperature	5	8%
	Total phosphorus	1	2%
swh	Dissolved oxygen	9	30%
	Fecal coliform	20	67%
	pH	1	3%

6.0 Estimation of Natural Variability

Evidence of the impacts of stressors on eelgrass is challenging to obtain, in part, because of the sensitivity of eelgrass to the natural variation in climate. The effects of stressors, especially mild or sub lethal ones, may not be readily distinguishable from the fluctuations that would be present in the absence of anthropogenic pressures. In this section we demonstrate an approach characterizing natural variability from time series of relatively undisturbed sites, which can then be used to determine when specific sites may be stressed beyond the extent of natural fluctuations. Data to fully use this approach are currently lacking, but we provide an example for a potentially stressed site using monitoring data from the Clinton ferry terminal.

Natural variability in eelgrass shoot density is defined as the annual change in shoot density in the absence of anthropogenic stressors or extreme geologic, climatic, or hydrologic events. Diefenderfer et al. (2011) suggest that it is almost impossible to measure the variability in ecological systems in the absence of human activity. Nearshore systems are continually responding to human alterations. However, Thom and Borde (1998) and Emmett et al. (2000) state that coastal estuaries in the Pacific Northwest may be among the least altered in the United States and represent valuable systems for studying natural variation. Estimates of natural variability provide a benchmark for comparison of the response of human-induced stressors or extreme events.

Some of the measured variability in shoot density comes from our inability to precisely define the extent of the eelgrass bed. Are isolated patches part of the bed and should the variability in occurrence of these patches be included in the estimate of natural variability? An 8-year study at Maury Island (Grette Associates, LLC 2008) evaluated the presence/absence of eelgrass within each 10-m x 10-m grid section (Figure 6.1) of three eelgrass beds (North Patch, South Patch, and Reference). This study was designed to assess the pre-condition of eelgrass beds to be compared to a later construction project. The results showed that most grid cells contained eelgrass for fewer than 6 years during the 8-year study (Table 6.1). Further, the least stable eelgrass was generally located on the edges of the bed (compare Figure 6.1 to Figure 6.2). This study also found that the coefficient of variation (CV) in shoot density was greater for cells in which eelgrass occurred during fewer than 6 years (mean CV = 43%) compared to cells in which eelgrass occurred for at least 6 years (mean CV = 27%). The core of an eelgrass bed can then be defined as the portion of the bed that has eelgrass occurring continuously over a number of years (e.g., six or more). This type of data collected from multiple sites could be used to refine the estimate of the core area which may be different by region or based on physical attributes.

Table 6.1. Presence/Absence Data for the Maury Island Gravel Dock Project (Grette Associates, LLC 2008)

Occurrence	Number of Cells Sampled			Percentage of Cells Sampled		
	North Patch	South Patch	Reference	North Patch	South Patch	Reference
Occurred 1 Year	33	57	17	14%	20%	5%
Intermittent (Occurred 2 – 5 years)	113	127	259	49%	45%	71%
Core (Occurred >6 Years)	86	100	91	37%	35%	25%
Grand Total	232	284	367	100%	100%	100%

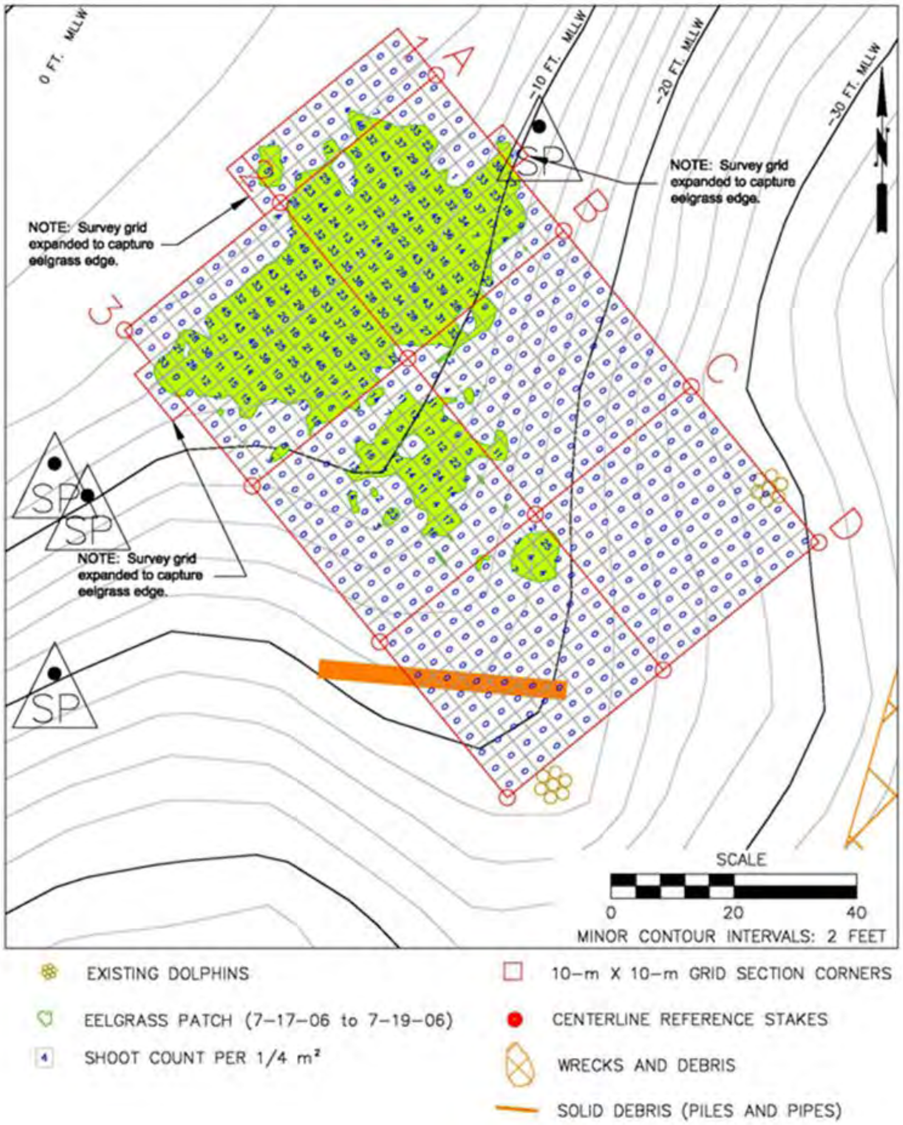


Figure 6.1. South Patch Sampling Grid for the Maury Island Gravel Dock Project (Grette Associates, LLC 2008)

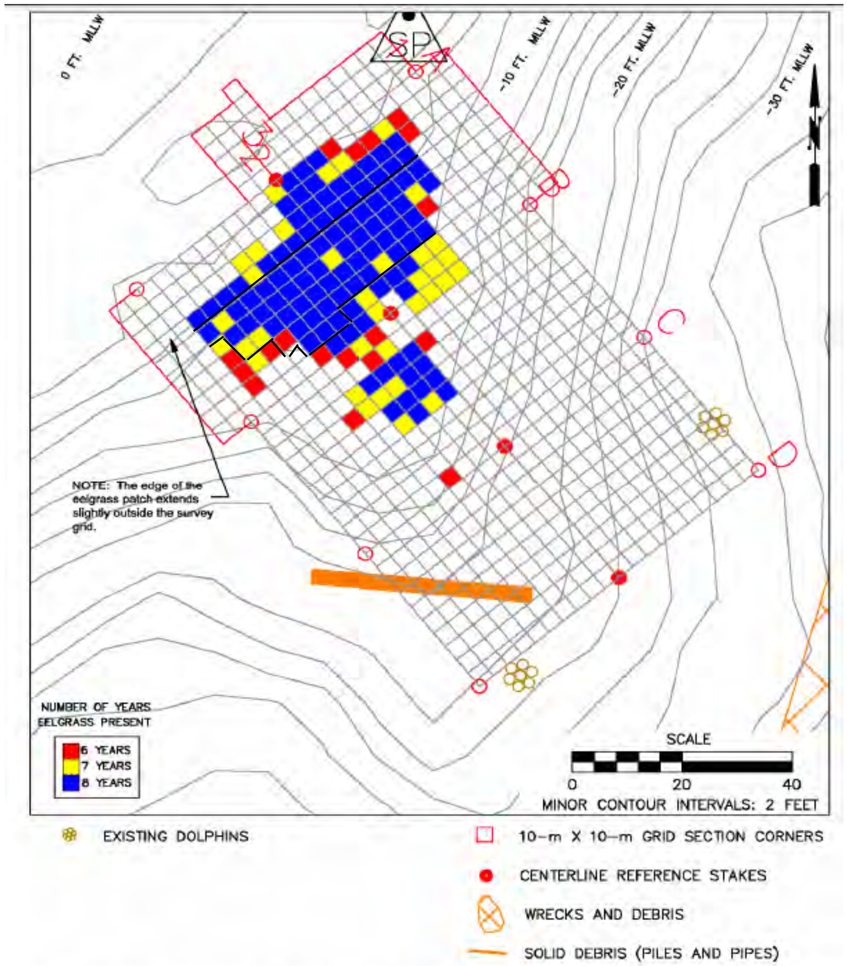


Figure 6.2. Number of Years Greater Than Five Where Eelgrass Occurred Within the South Patch Sampling Grid for the Maury Island Gravel Dock Project (Grette Associates, LLC 2008)

We compiled reference data from six multi-year studies to estimate natural variation in shoot density over time for a given site. For the purpose of this demonstration, we will assume that the data are taken from the core of the eelgrass bed. The data included three sites from the Maury Island Gravel Dock Project (Grette Associates, LLC 2008); eight reference sites from the Clinton Ferry Dock Eelgrass Restoration Study (Vavrinec et al. 2009); one reference site from the Sequim Wastewater Outfall Extension Project (Kyte and Evans 2002); six sites in Willapa Bay and four sites in Coos Bay from Thom et al. (2003); seven Puget Sound Eelgrass Monitoring sites (Berry et al. 2003); and three sites from the Global Seagrass Monitoring Network Project (http://seagrassnet.org/global-monitoring) (Figure 6.3). For comparison, a potentially stressed site from the Clinton Ferry Dock Eelgrass Restoration Study (Vavrinec et al. 2009) was evaluated separately.

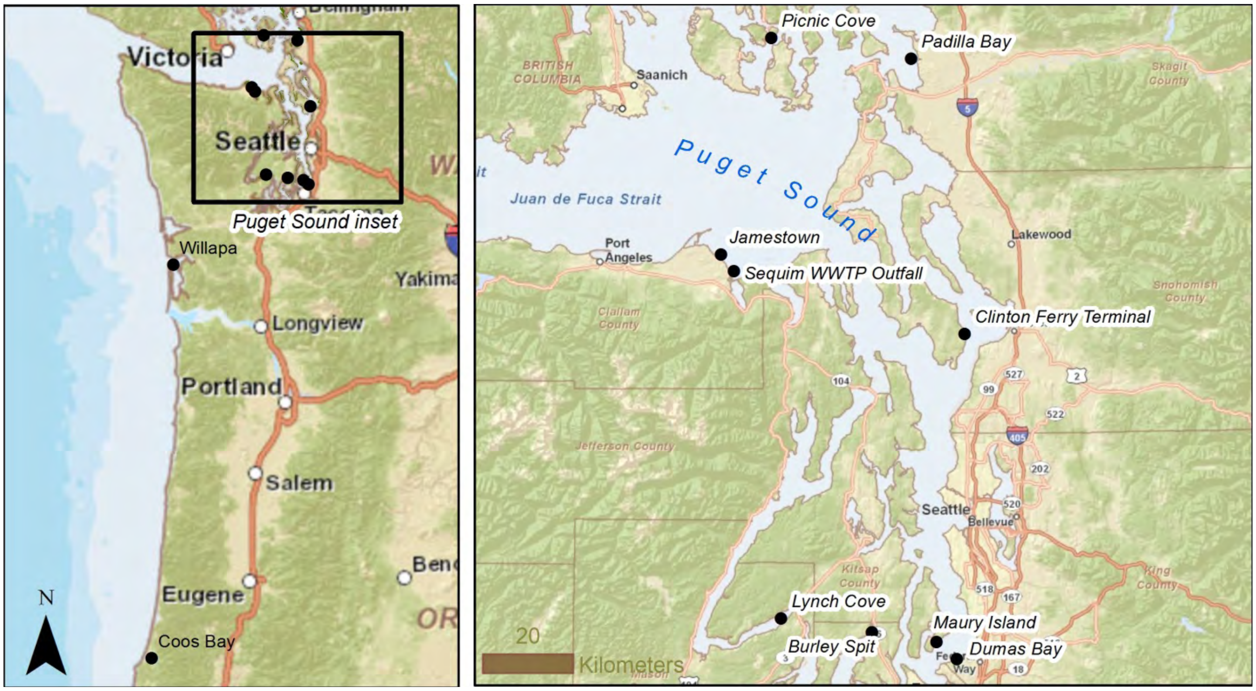


Figure 6.3. Locations of Studies Used in Natural Variability Analysis

For each data set, the CV was calculated over time for a given site (Table 6.2), among sites for a given year and study (Table 6.3), and among sites and over time for a given study (Table 6.4). Descriptive statistics are presented in Table 6.5. The third quartile of the observed data distribution for the CV over time within a site (57%) provides a nonparametric estimate of the upper bound of natural variability over time. The average variability among sites for a given year was significantly greater than the variability over time within a site and includes the variation in local habitats (ANOVA; d.f. 81; p = 0.005). The average variability over time and sites (CV = 38%; Table 6.5) was surprisingly small. The third quartile of the data distribution (58%) suggests that the variability is mainly reflecting changes in time rather than across sites.

The estimate of natural variability can be used to evaluate a time series of shoot densities from a given location. If the observed shoot density changes beyond what would be expected by natural variability alone, the site can be defined as being stressed. The Maury Island North Patch site and a potentially stressed site from the Clinton Ferry Dock Study were plotted against time with expected upper and lower bounds calculated from the mean ($\bar{x}$) of the time series plus or minus 1.96 times the standard error ($\widehat{\sigma_{\bar{x}}}$) where $\widehat{\sigma_{\bar{x}}} = \bar{x} \cdot \frac{0.57}{\sqrt{n}}$, where n is the number of years the site was observed (Figure 6.4) and the 0.57 is the estimated CV (natural variability) over time estimated from the reference data sets. The shoot density from Clinton Ferry Site A goes outside of the bounds derived from the estimated natural variability. Thus, this site can be viewed as being stressed.

Information about natural variability could be used as part of a process to determine the relative importance of eelgrass stressors. If a random sample of eelgrass beds in Puget Sound were studied over time for changes in shoot density and bed area, each time series could be compared to the estimated bounds associated with natural variability. If a determination of the key stressor could be made for each bed that was declared stressed and if the sample was representative of all stressors on eelgrass beds, then a ranking of stressors on Puget Sound eelgrass beds based on the estimated number of occurrences and the magnitude of loss could be made. The ranking of past and future stressors would have to be based on assumptions of past and future conditions.

Table 6.2. Mean Shoot Density (#/m^2) and CV Over Time for a Given Site

Study Location	Site	Number of Years Observed	Mean Density	CV Over Time at a Given Site
Maury Island	North Patch	8	10.6	33%
Maury Island	South Patch	8	22.3	57%
Maury Island	Reference	8	22.1	22%
Clinton Ferry North	A Ref	10	34.1	68%
Clinton Ferry North	B Ref	10	175.7	38%
Clinton Ferry North	C Ref	9	42.8	80%
Clinton Ferry South	D Ref	7	147.1	51%
Clinton Ferry South	E Ref	10	90.6	40%
Clinton Ferry South	E' Ref	10	86.7	48%
Clinton Ferry South	F Ref	7	17.5	78%
Clinton Ferry South	G Ref	9	47.2	89%
Sequim	Control	6	47.3	38%
Willapa Bay	Nemah	4	70.3	44%
Willapa Bay	NW Long Island	4	71.3	17%
Willapa Bay	Lewis Slough	4	66.2	44%
Willapa Bay	Paradise Pt.	4	44.6	36%
Willapa Bay	Jensen Pt.	4	47.1	63%
Willapa Bay	Toke Pt.	4	39.5	44%
Coos Bay	Bar View	4	128.0	18%
Coos Bay	Fossil Pt.	4	174.2	16%
Coos Bay	N. Bend Airport	4	94.2	24%
Coos Bay	Cooston Ch.	4	65.3	35%
Puget Sound Flats	Padilla Bay	3	172.7	13%
Puget Sound Flats	Picnic Cove	3	77.5	26%
Puget Sound Flats	Jamestown	3	51.1	64%
Puget Sound Flats	Lynch Cove	3	106.0	45%
Puget Sound Fringe	Dumas Bay	3	193.3	80%
Puget Sound Fringe	Burley Spit	2	364.7	22%
Dumas Bay	A (Shallow)	3	313.3	45%
Dumas Bay	B (Mid)	3	817.8	14%
Dumas Bay	C (Deep)	3	226.7	21%

Table 6.3. CV Among Sites for a Given Year

Study Location	Year	CV Among Sites for a Given Year	Study Location	Year	CV Among Sites for a Given Year
Maury Island	2001	54%	Clinton Ferry North	1997	96%
Maury Island	2002	45%	Clinton Ferry North	1998	63%
Maury Island	2003	13%	Clinton Ferry North	1999	154%
Maury Island	2004	23%	Clinton Ferry North	2000	111%
Maury Island	2005	32%	Clinton Ferry North	2001	109%
Maury Island	2006	39%	Clinton Ferry North	2002	86%
Maury Island	2007	63%	Clinton Ferry North	2003	83%
Maury Island	2008	61%	Clinton Ferry North	2004	98%
Willapa Bay	1998	55%	Clinton Ferry North	2005	71%
Willapa Bay	1999	25%	Clinton Ferry North	2006	138%
Willapa Bay	2000	29%	Clinton Ferry South	1998	37%
Willapa Bay	2001	24%	Clinton Ferry South	1999	37%
Coos Bay	1998	27%	Clinton Ferry South	2000	85%
Coos Bay	1999	35%	Clinton Ferry South	2001	78%
Coos Bay	2000	48%	Clinton Ferry South	2002	85%
Coos Bay	2001	55%	Clinton Ferry South	2003	59%
Puget Sound Flats	2000	60%	Clinton Ferry South	2004	65%
Puget Sound Flats	2001	73%	Clinton Ferry South	2005	71%
Puget Sound Flats	2002	38%	Clinton Ferry South	2006	63%
Puget Sound Fringe	2000	65%	Clinton Ferry South	2007	43%
Puget Sound Fringe	2001	9%	Clinton Ferry South	2008	64%
Dumas Bay	2008	52%			
Dumas Bay	2009	71%			
Dumas Bay	2010	97%			

Table 6.4. CV Among Sites and Over Time for a Given Study Area

Location	CV Among Sites and Over Time
Maury Island	36%
Clinton Ferry North	94%
Clinton Ferry South	63%
Willapa Bay	37%
Coos Bay	11%
Puget Sound Flats	11%
Puget Sound Fringe	44%
Dumas Bay	7%

Table 6.5. Descriptive Statistics of the CV over Time, Among Sites Within a Year, and Among Sites and Over Time

Variable	N	Mean	StDev	Minimum	First Quartile	Median	Third Quartile	Maximum
Over Time at a Given Site	31	42%	21%	13%	22%	40%	57%	89%
Among Sites for a Given Year	45	62%	31%	9%	37%	61%	81%	154%
Among Sites and Over Time	8	38%	30%	7%	11%	37%	58%	94%

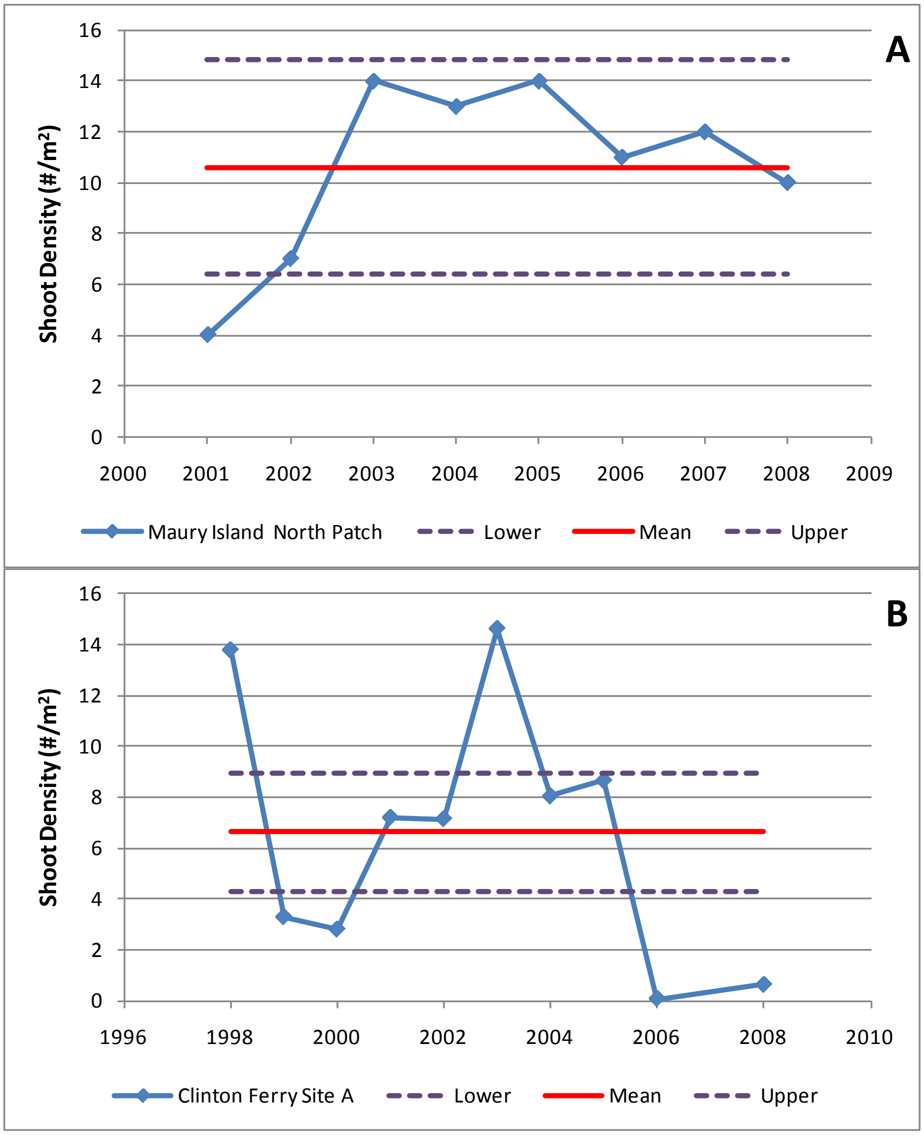


Figure 6.4. Shoot Densities over Time From a Reference (A) and a Potentially Stressed Site (B) Compared to an Expected Upper and Lower Bound Based on the Estimated Natural Variability in Shoot Density

7.0 Stressor Rankings

7.1 Explanation of Stressor Ranking Table

The ranking table (Table 7.1) incorporates a variety of information from expert opinion and published literature. Stressors are listed in the table according to the conceptual model in Figure 2.1, along with their controlling factors. The next five columns describe characteristics of the stressor and its impact on eelgrass. The characteristics and associated ratings are defined as follows:

- Magnitude: the effect of the stressor on a small area of eelgrass. High: the stressor generally kills eelgrass. Medium: the stressor has strong but sublethal effects, such that additional stresses will likely kill the plant. Low: mild sublethal effects that may limit growth or resilience of the plant but not lead to mortality without significant other stressors being present.
- Spatial extent: the relative amount of eelgrass habitat that is affected by the stressor. High: this stressor affects all or most of Puget Sound. Medium: the stressor affects large parts of Puget Sound. Low: effects are either very small in size or in a limited number of areas.
- Temporal extent: the time that eelgrass habitat is affected by the stressor. High: the stressor is persistent and continuous where it occurs. Medium: the stressor occurs regularly (e.g., every summer or during extreme tides) but is not continuously present. Low: the stressor occurs occasionally, on less than an annual basis.
- Reversibility: the degree to which the stressor can be removed (focusing on the physical ability to remove a stressor rather than the political likelihood of doing so.) High: the stressor can easily be stopped or removed and habitat will again be suitable for eelgrass. Medium: the stressor is difficult to remove and/or some habitat remediation is required. Low: it is not practically possible to remove or reverse the stressor, or changes to habitat are extensive and require extensive remediation.
- Trend: the pattern observed in the stressor from historical times to the present, and expected into the future. A stressor can increase, decrease, or remain the same.
- The case study evidence column indicates whether the stressor was identified as having an impact on eelgrass in case studies reviewed above. This information is not currently included in the total rankings because these studies focused on a subset of stressors as described in the case studies analysis and significant stressors are likely to be underrepresented.
- Uncertainty is incorporated into the ranking table via the second row of information for each stressor. Each characteristic receives a ranking: *** indicates this characteristic is well known through research; ** indicates there is some information about this stressor, but specifics may be unknown; and * indicates that information about this characteristic is primarily speculation or anecdotal.
- The global studies column indicates which authors of papers about global threats to seagrasses indicated a stressor to be of particular importance. D = Duarte 2002, O = Orth et al. 2006, SN = Short and Neckles 1999, SW = Short and Wyllie-Echeverria 1996, and W = Waycott et al. 2009. This information is also not included in the final ranking score.
- The stressor score is determined by assigned point values to stressor characteristic values. For most categories, High = 3, Medium = 2, and Low = 1, with the exception of the Reversibility category, in which High = 1 and Low = 3 (because high reversibility reduces the threat presented by a stressor).

The final stressor score is the mean of all of the points for each stressor, with a value of 3 (red) indicating the highest possible threat to eelgrass and 1 (green) the lowest. All columns included are currently weighted equally in the calculations.

- The knowledge score is the mean number of asterisks assigned to each stressor (not including case studies). A high knowledge score (3, green) indicates the most information is available about the stressor, while a low score (1, red) indicates very little information is available.

7.2 Rationale for Stressor Ratings

Here we describe the rationale we used to develop the ratings for the various stressors in Table 7.1. The general approach was to refer to published peer-reviewed literature for the region, published reports for the region, case studies, national and global literature, and local knowledge of experts (i.e., PNNL and DNR staff) in developing the ratings. In addition, the geospatial analysis of stressors detailed in section 5 allowed us to rate the spatial extent of some of the stressors. The ratings reflect our opinion based on the sources of information available. This is an initial effort to develop a tool that can be updated and adapted over time as new information becomes available. By grouping the ratings into three qualitative categories (i.e., low, medium and high), we acknowledge the uncertainty in all the ratings.

Invasive species – We considered *Zostera japonica* to be the primary non-native invasive species of concern (Mach et al. 2010). Although *Z. japonica* is common, it appears to be having a limited effect on the native *Z. marina*. Case studies in the region show that *Z. marina* has a competitive advantage because of its size and its ability to hold space. There is some evidence that *Z. japonica* is increasing in cover and distribution. Therefore we consider the magnitude and extent of the threat to be medium, but increasing. Once *Z. japonica* is removed either naturally or experimentally, it appears that *Z. marina* can re-colonize the space.

Nutrient-driven harmful algal blooms – We view harmful macroalgal blooms as an increasing problem in the Sound. Case studies indicate that macroalgal blooms driven by inorganic nutrients discharged from local watersheds can result in the deposition of masses of macroalgae that are harmful to eelgrass and other nearshore organisms. The role of phytoplankton blooms causing damage to eelgrass is much less certain because of the lack of research. Phytoplankton production can be nutrient-limited in the summer in nearshore areas, and nutrient additions can support a bloom that increases turbidity and reduces eelgrass health and growth rates. Hence we suspect that there is a need to further study the role of nutrient additions in forming phytoplankton blooms in nearshore areas occupied by eelgrass. Also, the role of land use practices in contributing to nearshore nutrients need further research (Bricker et al 2004).

Suspended sediment – Water clarity in nearshore areas is often reduced by the presence of suspended sediments, which can reduce the light input to eelgrass beds below that required for eelgrass growth. Berry et al. (2003) showed that suspended sediments, which can make up the primary component of turbidity in Puget Sound, proved to be more important than chlorophyll a-driven turbidity in explaining eelgrass distribution there. Studies in Puget Sound and elsewhere document that suspended sediments from land use actions can increase nearshore turbidity for extended periods, leading to a high ranking for temporal extent. Levels of suspended sediment may drop if inputs are reduced, but due to the variety of inputs, reversing the stressor can be moderately difficult. This topic needs further research especially in regard to land use practices.

Sea level rise – The sea level is rising in central Puget Sound faster than the global eustatic rate because of land mass subsidence. The relative rise rate varies throughout Puget Sound. Based on global estimates, the rise rate should increase as global temperatures increase. The resulting increased depth and light attenuation may contribute to vulnerability of eelgrass and/or result in eelgrass decline at the lower edges of beds. The response of eelgrass may be to move upslope if there are suitable areas available. Although a higher sea level will probably affect eelgrass throughout Puget Sound, the actual effect is very uncertain, and will interact with stressors that act upon water clarity. As climate effects are not under local control, the stressor itself can not easily be reversed, but some mitigation may be possible.

Overwater structures – The local case studies and publications document the direct and indirect effects of overwater structures on eelgrass, which generally cannot survive below or in some cases near the structures. Structures can be removed with eelgrass recovering if other conditions (e.g., substrata quality) have not been extremely altered. Our analysis of spatial extent of overwater structures shows that they cover only a very small area of the Sound, but we expect that area to increase in the future.

Aquaculture – Aquaculture activities we considered were those associated with shellfish, including clams and oysters. Impacts of these activities on eelgrass have been studied to a limited degree in Puget Sound. Aquaculture is not widespread and therefore received a low spatial extent score, but can contribute to eelgrass declines if not done in a manner that takes eelgrass into account. Operations and impacts range from seasonal to longer term.

Bioturbation – This is essentially unstudied in any systematic way in Puget Sound. Case studies in Puget Sound have documented crabs and seastars disrupting meadows through burial and foraging. Bioturbation is an issue in other regions of the world. We have no reason to believe that this stressor will increase or decrease in Puget Sound. Crabs and seastars were very abundant near docks, and were observed feeding on the fouling community attached to the pilings, potentially contributing sublethal stress in these locations.

Storms – Our observations and those of others corroborate the fact that large storm events that generate high winds can disrupt large areas of eelgrass, causing mortality and changes in substrate. After major storms, piles of eelgrass are observed on beaches. We have also observed a relatively rapid recovery of meadows where we have conducted other research. The spatial extent was difficult to estimate but we expect that a moderate number of meadows in the region are affected by storms occasionally.

Construction – Case studies at the Clinton ferry terminal and in areas where the nearshore is excavated to lay a pipeline or cable disrupts and kills eelgrass. Although the magnitude of the disruption is high, other stressor characteristics are ranked as low because these events are generally limited in space and time. Reversibility appears to be moderate (K. Starke, King County, personal communication 2010) and is enhanced with some intervention in the form of careful backfilling and by planting eelgrass in the backfilled area. Construction will likely increase over time as the human population increases.

Boat grounding/anchoring – Barge groundings have damaged eelgrass at the Clinton ferry terminal and at Hood Canal Bridge, as well as smaller scale impacts near marinas. Anchor-chain impacts in eelgrass have also been documented. Both actions result in loss of eelgrass. We believe that these effects have a low spatial extent, but they have not been comprehensively accounted for in the Sound and are likely to increases as boat traffic increases. Because of sparse objective data here, coupled with the global literature indicating a widespread problem, we believe that this characteristic needs more research in Puget Sound.

Shoreline armoring – Based on a recent review of shoreline armoring in Puget Sound (Shipman et al. 2011), there appears to be very little documented impact on eelgrass from armored shorelines, with the possible exception of areas that are highly developed. However, studies on this topic are very sparse and not highly focused. The long-term studies at Lincoln Park in west Seattle illustrate that eelgrass will eventually be affected by substrata changes that are associated with reduction in fine sediment delivery to the beach. Further, eelgrass did recover over time once sediment was artificially re-introduced to that beach by placement. Our conclusion from the available data is that the degree of impact will vary considerably depending on the characteristics of the site and the extent of armoring and available sediment in the surrounding area. A substantial amount of shoreline is armored, and once armored the impact will be long term. Reversibility is possible when sediment is reintroduced.

Dredging/filling – There are clear examples in Puget Sound where dredging or filling have resulted in the long-term loss of eelgrass. The spatial extent is medium and largely found in deltaic areas that have undergone development. Reversibility is possible if the depth strata and substrata at a site are restored.

Propeller wash/boat wake – Investigations and observations in Rich Passage and in other areas show that propeller wash can erode substrate in eelgrass beds and wakes from ships can be large enough to scour beaches and erode eelgrass. The spatial extent is low but we are uncertain because of the lack of data. Because this stressor is short in duration but can be frequent where it occurs, we rated the temporal extent as medium. However, the propeller wash at ferry terminals was shown to be frequent and probably resulted in the permanent loss of some eelgrass. Once the wash is removed, we suspect the substrata and eelgrass to recover if sources of material are available to the site.

Anthropogenic contaminants – The effects of contaminants on eelgrass in Puget Sound have not been studied, so our knowledge of the effects on eelgrass is highly limited. The geospatial analysis showed that contaminants are widespread in the Sound but may be highly diluted in areas far from point discharges. This topic needs further research from the standpoint of negative effects on the plant as well as uptake by eelgrass and incorporation into the food web.

Disease – The primary disease we evaluated was wasting disease. We and others have observed the presence of wasting disease in eelgrass populations throughout most of Puget Sound. At present it appears to not have a detrimental effect on survival of these populations, but we are unsure because of the paucity of studies in the region. Because the disease may increase with changes in sea temperature and salinity, the problem may increase. Eelgrass can recover once conditions improve, but the recovery may take decades, as seen on the east coast of the U.S. following the near extirpation of eelgrass from the disease in the 1930's. Research would help resolve the issue of the potential rise in the disease, and the extent to which recovery or increases in eelgrass will be affected by disease.

Organic matter discharge/sulfides – The deposition of organic matter in the nearshore can occur by several mechanisms including storm water, log rafting, tree debris, macroalgae piles, etc. If organic matter is thick enough, the sediment porewater will become anaerobic. In this process hydrogen sulfide is developed which is toxic to eelgrass. We expect that the spatial extent is low based on the spatial analysis of discharges, and temporal and reversibility are medium based on literature from other regions, but the lack of data make these ratings speculative.

Sea temperature rise – This generally refers to the warming of water through climate change. The literature shows that temperature directly affects the productivity and respiration rates of eelgrass. Extended periods of high temperatures reduce eelgrass growth and survival, and can effect large areas of the Sound. In places where the water warms substantially in the summer (e.g., poorly flushed shallow bays) small increases in the temperature would result in loss of the plants. In the case of climate change driven sea temperature increases, the reversibility would be low. This factor has been highlighted repeatedly in the global literature, but remains poorly understood in Puget Sound.

Freshwater input – This stressor refers to changes in freshwater delivery to the nearshore environment, which can occur through land use changes, climate change, development of hydropower facilities, and other causes. Freshwater flow affects salinity in the nearshore as well as the delivery of nutrients, contaminants, and organic matter. Eelgrass can grow in a relatively wide range of salinities. The literature shows that salinities below about 5 psu will kill eelgrass is the salinity is maintained for long periods (e.g., months). The literature also shows that a specific anomalous combination of salinity and temperature interacted to produce a massive outbreak of wasting disease on the east coast of the U.S. Because of a lack of work on this topic in the region, we have generally low certainty about the temporal extent and reversibility of the effects of the stressor. It is also likely that increases in freshwater input in some areas or times may occur alongside decreases in other cases. We expect that large changes in climate could affect salinity in the broader Puget Sound region.

Overfishing – The global literature has indicated that overfishing can have a top down effect on seagrasses. There is a chance that overfishing produce a cascade of impacts that eventually could jeopardize eelgrass through the loss of grazers that remove epiphytic algae from the leaves, contributing to low level stress on the plant. Because of the lack of local investigations we are uncertain about any of the characteristics of this stressor, but expect that the effects can be moderate in spatial extent and require some time, and perhaps intervention, to recover.

Table 7.1. Stressor Ranking Table

Stressor	Controlling Factor	Magnitude	Spatial Extent	Temporal Extent	Reversibility	Trend	Case Study Evidence	Global Studies	Threat Score	Knowledge Score
				Characteristics of Stressor						
Invasive species	Competition	Low **	Med **	Med **	Med *	Increase **	Direct *	O	**2.00**	**1.80**
Nutrient-driven harmful algal blooms	Competition, light	Med **	Med *	Med *	Med **	Increase *	Direct *	SW, W, D, O	**2.20**	**1.40**
Suspended sediment	Light	Med ***	Med *	High *	Med **	Increase *	Direct *	SW, D, O	**2.40**	**1.60**
Sea level rise	Light	Med **	High *	High *	Low ***	Increase *	None	SN, D, O	**2.80**	**1.60**
Overwater structures	Light	High ***	Low ***	High ***	Low ***	Increase **	Direct ***		**2.60**	**2.80**
Aquaculture	Light, substrate	Med **	Low **	Med *	Med *	Increase **	Direct ***		**2.00**	**1.60**
Bioturbation	Substrate	Low *	Low *	Low *	Med *	Same *	Direct, spec. **		**1.40**	**1.00**
Storms	Energy	High *	Med *	Low *	High **	Increase *	None		**2.00**	**1.20**
Construction	Substrate, direct	High ***	Med ***	Med *	Med **	Increase *	Direct ***		**2.40**	**2.00**
Boat grounding /anchoring	Direct	High **	Low *	Low *	High *	Increase *	Direct *	W	**1.80**	**1.20**
Shoreline armoring	Substrate, energy	Low *	High ***	High *	Med *	Increase *	Ambiguous *		**2.40**	**1.40**
Dredging/ filling	Substrate, direct	High ***	Med **	High ***	Med **	Increase *	Direct **		**2.60**	**2.20**
Propeller wash/ boat wake	Energy	Med **	Low *	Med *	High *	Increase *	Direct/Ambiguous *		**1.80**	**1.20**
Anthropogenic contaminants	Direct	Low *	High **	Low *	Low *	Increase **	None	SW	**2.20**	**1.40**
Disease	Direct	Low *	High *	Med *	Med **	Increase *	None *		**2.20**	**1.20**
Organic matter discharge/sulfides	Direct	High **	Low *	Med *	Med *	Same *	Direct *		**2.00**	**1.20**
Sea temperature rise	Temperature	Med *	High *	Med *	Low **	Increase *	None	SN, O	**2.60**	**1.20**
Freshwater input	Salinity	Med **	High **	Med *	Med *	Same *	None *		**2.20**	**1.40**
Overfishing	Herbivory	Low *	Med *	Med *	Med *	Same *	None *		**1.80**	**1.00**

8.0 Recommendations

In this section we detail our recommendations regarding stressor research that would help inform management actions required to protect and restore eelgrass in Puget Sound. Further, we provide recommendations toward accomplishing a 20% increase in eelgrass by the year 2020.

8.1 Stressor Research Priorities for the Puget Sound Region

The recommendations regarding stressor research priorities are based on our review of the available information. They are intended for the broader research community.

The scientific uncertainty is large for most of the stressors we discuss. To develop Table 7.1, we used a simple numerical method to provide a ranking of stressors based on measures of impact and degree of uncertainty. Hence, the highest priority topics for research are those that are both important and uncertain. Using the numerical rankings, we can divide the stressors into groups according to the threat score and knowledge score, as shown in Table 8.1.

Table 8.1. Categorization of Stressors by Threat and Knowledge Rankings. Within categories, stressors are listed from high to low threat scores.

		Knowledge Score	
		Low (<2)	High (>= 2)
Threat Score	High (>2)	Sea level rise, sea temperature rise, suspended sediment, shoreline armoring, nutrient-driven harmful algal blooms, anthropogenic contaminants, disease, freshwater input	Overwater structures, dredging/filling, construction
	Moderate to low (<= 2)	Invasive species, aquaculture, storms, organic matter input/sulfides, boat grounding/anchoring, propeller wash/boat wake, overfishing, bioturbation	None

In the following, we describe the categories above as three priority groups:

- ***Research Priority Group 1***: High threat with low knowledge – a) sea level rise, b) sea temperature rise, c) suspended sediment, d) shoreline armoring, e) nutrient-driven harmful algal blooms, f) anthropogenic contaminants, g) disease, h) freshwater input
  - These stressors affect broad areas, appear to be increasing, and will need to be considered when making management decisions at the landscape scale. As knowledge is relatively low, better understanding of these stressors and their interactions will improve eelgrass management. Most stressors in this category are recognized in the global threats literature and by strong local scientific opinion in the Puget Sound region. Almost all affect the health and growth of eelgrass through effects on water properties. This fact and the numerous interactions between these stressors

contribute to the difficulty of determining the relative importance of each. This also implies that preventing further degradation of water quality could lead to significant recovery of eelgrass and that reductions in some stressors could help alleviate the impact of others. For example, reducing sediment loads and algal blooms could help offset the effects of sea-level rise. Predicting the extent of stress and loss of eelgrass caused by these stressors, as well as the level of recovery to be expected from different management actions requires a much better understanding of the mechanisms and interactions. Research on tolerance levels for freshwater input, anthropogenic contaminants, and sulfides is needed for the region's eelgrass. In particular, salinity tolerances are not well understood in terms of the variation driven by freshwater flows and tides.

  – Shoreline armoring is an exception in this group, as it primarily affects substrate and wave energy rather than water quality. However, the degree and mechanisms of impact are poorly known despite the prevalence of armoring. In fact, there appears to be much spatial variation in the degree of impact from armoring on eelgrass. Understanding the spatial patterns and mechanisms of disturbance would inform decision makers regarding where armoring can be placed with minimal damage to eelgras, and where armoring could be removed or modified to help eelgrass recover. This research could guide the design of armoring alternatives in the future.
  – Anthropogenic contaminants deserve special recognition because their effects on eelgrass are very poorly studied here and elsewhere. While a number of contaminants (e.g., trace metals, organics, oil spills) have been monitored and documented in Puget Sound, and eelgrass is thought to accumulate and transfer some contaminants through the food web, no work on this topic has been conducted in the region.

- ***Research Priority Group 2:*** Moderate to low threat with low knowledge – a) invasive species, b) aquaculture, c) storms, d) organic matter input/sulfides, e) boat grounding/anchoring, f) propeller wash/boat wake, g) overfishing, h) bioturbation
  – These stressors are thought to be less of a threat to eelgrass than those in Group 1. The uncertainty about these stressors, however, is high, which means that the true extent of their effect on eelgrass is unknown and could be higher than currently thought. The need for research about these stressors is less pressing than for Group 1 stressors, but may still be useful for determining management priorities and predicting eelgrass dynamics and recovery. In addition, stressors in this group may be less important but more straightforward to manage (e.g. aquaculture and boat activity vs. sea temperature or level rises), thus resulting in potentially significant improvements in eelgrass health. Additionally, many of these impacts are less widespread than those in Group 1, but may have strong impacts on local sites that could recover with improved understanding of management needs.
- ***Research Priority Group 3***: High threat with high knowledge – a) overwater structures, b) dredging/filling, c) construction
  – These stressors are known to have direct and strong impacts on eelgrass. Compared to topics in Research Priority Group 1, the knowledge about many of these stressors is more extensive. For example, overwater structures are well documented to have direct, significant and long-term effects on eelgrass, though the spatial extent of overwater structures is relatively small. Because the knowledge about these stressors is high, it is relatively straightforward to predict that removing them will reverse of the effects on eelgrass and allowing them to increase will result in predicable losses of eelgrass. This is in contrast to shoreline armoring as discussed above, which is widespread but less well understood in terms of effects on eelgrass and how to minimize adverse effects. The

research needs for these stressors are lower than those for the first two groups due to the amount of information already available.

8.2 Recommendations to Managers for Attaining a Net Increase in Eelgrass Area

The global literature strongly points to the overriding influence of human population driven land use changes and management practices in causing the loss of seagrasses. The case studies we reviewed verify that these influences are threats to the seagrasses of Puget Sound. Further, there is a growing body of literature on the potential changes in seagrasses associated with climate change.

The stressors summarized in Table 7.1 for Puget Sound can be linked to land use change, climate change, and management actions. Our spatial analysis (section 5) revealed that stressor magnitude and spatial extent varied among the seven regions of Puget Sound. Regions such as the San Juan Islands and the Strait of Juan de Fuca had relatively low stressor levels because of low population growth and density, as well as less historical development. In comparison, the central Puget Sound region has undergone intense population growth and harbors a high population density. Associated impacts included substantial coastal and watershed development and suspected eelgrass losses. In general, logging and agriculture affected all of Puget Sound historically and are still having an impact in many regions. Because population influences land use practices and land use practices affect the quality of the environment for eelgrass, it is clear that land use management decisions could reduce eelgrass stressors and result in recovery of eelgrass. Note, however, that regions with low relative stress, such as the San Juan Islands, still exhibit localized losses of eelgrass, so cannot be ignored even if population and land use pressures are not as intense.

There is a set of principles from ecosystem restoration (Thom et al. 2011) that can be applied directly to Puget Sound where the goal of the Puget Sound Partnership is to expand eelgrass area by 20% by 2020. This net increase will require the following: (1) effective protection of existing meadows; (2) enhancement of existing meadows; (3) restoration of historical meadows; and, (4) creation of eelgrass meadows where none existed historically. Creation, however, will succeed only if site conditions have changed to become favorable for eelgrass. In addition, science-based actions must be taken relative to the increasing magnitude and spatial extent predicted for many of the stressors. Development and self-maintenance of an eelgrass meadow requires a relatively healthy “landscape” which supports habitat forming and maintaining processes. For example, increased development of a watershed often leads to enhanced turbidity and shoreline structures. These changes cumulatively threaten the existence of a restored eelgrass meadow at the base of that watershed. Therefore, restoration, enhancement and creation and protection actions are directly dependent on the quality of the surrounding landscape.

The information in Table 7.1 can help in decisions about what stressors to examine to support management actions that will facilitate *protection* and *restoration*. The most relevant characteristics of stressors are *magnitude*, *spatial extent*, *trend* and *reversibility*. If we assume that most stressors are increasing over time, then the strength and spatial extent become very important prioritizing factors. The ability to reverse the damage through management actions also is important. A high score for reversibility means that recovery is relatively easily facilitated, whereas a low score means that a high level of intervention is needed. *Protection actions* would be best applied to those stressors that have moderate to high magnitude and spatial extent, and low to moderate reversibility. These include nutrient-driven harmful algal blooms, suspended sediment, sea level rise, construction, dredging/filling, sea temperature rise, and freshwater input. The stressors with a low to moderately low knowledge score indicate that there is need of more research to support management actions. The stressors with low reversibility that require more research include *nutrient-driven harmful algal blooms*, *suspended sediment*, *sea level rise*, *sea temperature rise*, and *freshwater input*.

Protection tactics include –

Minimize project-specific losses of eelgrass by strongly enforcing avoidance and mitigation requirements related to known stressors

Evaluate the degree to which best management practices affect eelgrass beds (i.e., how effective is dock grating?).

Prevent new point and non-point discharges that degrade water quality.

Ensure that land is available to accommodate a shift in elevation and location of eelgrass that may be driven by sea-level rise.

Develop a tracking measure: proportion of hydraulics project approval permits, county permits or DNR leases that allow/deny impacts to eelgrass.

To restore eelgrass requires a clear understanding of why eelgrass no longer exists at a site. Once this is understood, actions can be taken to alter conditions to improve conditions for eelgrass.

Stressors that result in damages that are moderately to easily reversible but that have a low to moderate knowledge score should be studied. Stressors that have a high to moderate magnitude and spatial extent may, if removed, result in a relatively large change in eelgrass. As an example, Dowty and Ferrier (2009) provided a broad estimate of where light is adequate to support eelgrass in Puget Sound relative to where eelgrass actually now exists. We recommend that areas where no eelgrass exists, but where light is adequate, should be investigated further to understand the factors limiting eelgrass restoration. In addition, a further assessment of how water clarity could be increased in general in Puget Sound to improve light conditions for eelgrass should be conducted, and management actions to facilitate improved light conditions should be developed.

Investigations of potential restoration sites often reveal localized (i.e., low spatial extent) stressors such as overwater structures, armoring, boat groundings, and small stormwater discharges. Hence, site-specific research must be included in any restoration planning effort.

- Restoration tactics include –
  - Restore nearshore processes through individual projects in degraded areas, which are likely to lead to eelgrass expansion. Examples: Elwha River restoration, Nisqually River restoration, Skokomish estuary restoration.
  - Conduct site-specific research to identify and rectify any significant eelgrass stressor that could affect the restoration project.
  - Prior to full planting, utilize experimental plantings to evaluate the suitability of the site following stressor abatement.
  - Restore eelgrass beds in appropriate areas through transplantation. Develop site evaluation criteria that include consideration of local stressors. Develop a goal of ‘acres of eelgrass planted’ similar to that adopted in the Chesapeake Bay.

- Improve water quality though improved discharge management and TMDLs. Conduct feasibility analyses to assess potential for regional eelgrass expansion associated with water quality gains.
- Develop a tracking measure: the success of the restoration projects over five years using quantitative metrics and performance criteria.
- Record lessons learned from each project in a manner that they can be applied to improve restoration in the future.

8.3 Recommendations to the WDNR Eelgrass Stressor-Response Project

At present the DNR monitoring program does a very good job of estimating the overall change in eelgrass area in the Puget Sound. However, the sampling methodology was not designed to quantify local-/smaller-scale changes at the reach or perhaps at the sub-basin scale—the scales at which many stressors act.

The eelgrass stressor-response research program should develop key questions for further targeted investigation. We believe that answers to these key questions should provide 1) highly relevant scientific information that underpins management decisions, 2) methods to measure eelgrass health as an indicator of ecosystem health, and 3) recommendations for what is needed to increase the coverage of eelgrass Sound-wide in accordance with the new state restoration target. The population growth rate in the region and the world will not decline in the foreseeable future, so the research program needs to address stressors associated with alterations in land use and land cover, introduction of contaminants, and broader regional and global stressors associated with climate change.

Our above assessment of stressors suggests that, through implementation of the following recommendations, the Eelgrass Stressor-Response Project could 1) better address its goal, 2) integrate the SVMP monitoring program with the eelgrass stressor-response program, and 3) provide critical guidance to the Puget Sound Partnership’s eelgrass restoration goal of expanding eelgrass area by 20% by 2020.

1. *Characterize sites that have lost substantial amounts of eelgrass*. In most cases, most large losses of eelgrass remain unexplained. We suspect that there is a physiological basis for these losses that possibly relates to shifts in water properties driven by alterations in circulation, water residence time, turnover, stratification, etc. Characterizing the conditions of the controlling factors at potential restoration sites is the first step in identifying actions needed to improve conditions for eelgrass. This includes the potential sources of new recruits to the sites.
2. *Focus on the stressors that will affect management decisions most directly*. Because many management decisions are made through land-use regulations, and changes in land use and land cover can affect water quality and nearshore physical structure development (e.g., overwater structures, seawalls), it is important to clearly identify the types of changes in land use that will result in alterations in factors affecting eelgrass. For example, how will changing from rural to highly urbanized land use affect nutrient runoff, harmful algal blooms, and water temperature and water clarity? Analysis of factors that have a clear connection to plant growth and survival should be undertaken. This is especially true for those factors that potentially exert broad geographic control over eelgrass such as water clarity, water temperature and nutrient-driven harmful algal blooms.

3. *Define eelgrass health using terms such as plant vigor*. Because eelgrass condition is used as a contributing factor in assessing the health of Puget Sound, it is reasonable for the health of eelgrass to be defined in quantifiable terms. Plant health is often described in terms of plant vigor. Plant vigor can be quantified as biomass, chlorophyll a content, growth rate, flowering and viable seed production, and below-ground biomass. Relate eelgrass health to the metrics collected in the monitoring program.

8.4 General Recommendations Regarding Eelgrass Stressor Research in Puget Sound

Based on our review of the regional information and literature, as well as the global literature on seagrasses, we developed the following general recommendations regarding eelgrass research in the Puget Sound region.

- *Develop an organizing numerical model*. The model can be used to integrate the understanding of factors affecting eelgrass growth and abundance and to predict future eelgrass conditions. There is a urgent need for a tool to predict the effects of management actions, local and regional variations, loss of eelgrass, and to help identify critical uncertainties and targeted research questions. Use of a linked set of models, including a hydrodynamic model, water properties model, and eelgrass growth model, would allow scientists to explore the stressors that potentially contributed to the loss and at what level stressors acted. This would allow specific research questions to be developed, which could then be addressed with experiments and monitoring.
- *Develop a relationship between monitoring data collected and the numerical model*. The objective is to better link the monitoring data with regional management decisions through the numerical model. For example, if *area* is the selected eelgrass metric, make sure *area* is explicitly modeled.
- *Adjust aspects of monitoring programs to better link with the numerical model at a scale and resolution at which many stressors act*. This could mean adding a mapping component that could be used to fully delineate patches of a certain minimum area and shoot density.
- *Investigate stressors associated with climate change*. Recent work in the Pacific Northwest and elsewhere globally strongly suggests that climate change presents a real threat to eelgrass in the region. Climate variation strongly influences water properties and sea level. In addition, climate change coupled with changes in land use and land cover could act to reduce the physiologically based eelgrass carrying capacity of Puget Sound.
- *Use an integrated research framework for investigating stressor effects both potential and realized*. The most certain results often come from an integration of field observations, monitoring, field experiments, laboratory (i.e., controlled bench scale and mesocosm scale) experiments, and numerical modeling. For example, the Westcott Bay research used field observations and field experiments to investigate losses of eelgrass. To date it has been difficult to pinpoint the cause of the losses. Use of a linked set of models would help explore potential causes and re-focus studies.
- *Establish an intensively studied reference ecosystem where eelgrass is abundant*. Monitoring an area intensively for water properties, eelgrass metrics, weather conditions, light, etc., over the

long term can provide a wealth of information for understanding what drives variation in eelgrass health. The longer-term monitoring done at various sites in Puget Sound has shown a large variation in eelgrass density annually, which appears to be related to broader regional climate variation and oceanographic conditions. An intensively monitored ecosystem would provide this basic set of information on natural variation. This data set would also provide data for refinement of a numerical model of eelgrass. Comparing intensively monitored ecosystem to other areas, such as Padilla Bay, that receive systematic monitoring would result in a very powerful data set on natural variation.

- *Consider population vulnerability and resilience*. It is clear that local selection and adaptations favor certain phenotypes, degree of flowering, and perhaps overall population genetic diversity. These differences can result in variation in the resilience of local populations. Thus, climate change may have a large effect on populations in shallow bays that have restricted circulation and marginal conditions for eelgrass. Furthermore, the "tipping point" for populations can be both experimentally evaluated and modeled. Sources of renewal of populations should also be studied. Monitoring vulnerable populations and tipping points may provide the earliest indication of regional issues.
- *Systematically investigate appropriate and highly successful eelgrass restoration protocols and procedures*. Although much has been done in Puget Sound and elsewhere, the nuances of genetic stock, sediment conditions, and planting density and technique still can be improved. Define clear criteria of success for restoration projects based on new research. Define and assess the functional metrics associated with restored meadows. Use the numerical model to help select restoration sites that have a high potential for success. Conduct restoration in an adaptive management framework to improve success.
- *Consider eelgrass restoration as part of a carbon management strategy.* Several recent reports have documented the importance of coastal habitats, including seagrasses, for sequestering carbon dioxide (e.g., Murray et al. 2011). These reports show that restoration of extensive areas of lost coastal habitats can capture significant amounts of atmospheric carbon emissions. We have had informal discussions with agencies and individuals regarding restoration of eelgrass in the North Pacific for the purpose of sequestering carbon. Right now, data are scarce regarding the dynamics and amounts of carbon seagrasses can sequester in the Northwest. Focusing some research effort on quantifying carbon capture and the fate of captured carbon would provide useful information for more accurate estimates of carbon sequestration.

8.5 Closing Comments

Eelgrass serves as a focal habitat for perhaps hundreds of species in the Sound. These species benefit directly or indirectly from the structure and processes provided by eelgrass. Eelgrass inhabits the nexus between the land and the Sound, where anthropogenic development and the many attendant stressors are concentrated. It is clear that stressors have resulted in loss of eelgrass in specific locations. Some of the stressor mechanisms are obvious and need little new research. However, there are a large number of other stressors that require research to better understand the level and mechanism of effect on eelgrass in order to explain losses and predict the effects of stressor abatement on eelgrass recovery. We cannot easily explain relatively large declines in eelgrass in some regions of the Sound. This is surprising because the science of seagrasses is relatively well developed. This means that in order to restore eelgrass, further work is needed to parse out the single and cumulative impacts of stressors. Global losses of seagrasses are now documented, with 14% of all seagrass species at elevated risk of extinction (Short et al 2011). Many of the threats identified in the global literature are active in the Sound, and we expect these threats to grow with time. The goal of a net increase in eelgrass in the Sound is an important one. To realize this goal, eelgrass must be protected from existing and new threats, and research on how and where to restore eelgrass is critical.

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Appendix A

Details of Case Studies

Appendix A

Details of Case Studies

A.1 Rich Passage

Description of site: Bainbridge Island nearshore sites north of Rich Passage and Port Orchard nearshore sites south of Rich Passage

Reference: Woodruff et al. 2001

- *Why studied*: Assessment of passenger-only ferry wake
- *When*: Study in 2000, compared to mid/late 1970s
- *Study looked at*: Cover and health of eelgrass beds in areas potentially affected by ferry wake, as well as controls
- *Findings—eelgrass trends*: Approximately 44% decline between 1979 and 2000, but earlier study potentially underestimated subtidal. Significant change in location of beds.
- *Findings—eelgrass stressors*: Declines in areas receiving impacts from ferry wakes, but also areas that are probably affected by ferry wake have eelgrass that was not there in 1979. Upper edges of beds exposed to wave action regularly and show erosion. Declines in sites that were considered to be controls not affected by wake. Ferry wake may contribute to changes in eelgrass, but cannot explain observed patterns.

A.2 Grays Harbor

Description of site: Shell plots created for crab nursery habitat damaged eelgrass, which was then transplanted into ponded areas

Reference: Thom 1995

- *Why studied*: Monitor progress of transplanted sites
- *When*: 1990-1995
- *Study looked at*: Progress of transplanted eelgrass in shell beds created for crab nursery habitat
- *Findings—eelgrass trends*: Shells originally killed off eelgrass; transplants in ponded areas did okay for first 4 years, some decreased in last year.
- *Findings—eelgrass stressors*: Original placement of shells definitively killed eelgrass. Transplanted plots in ponded areas within shell beds did okay. Sedimentation at edge of transplanted eelgrass plots killed some eelgrass.

A.3 Purdy Spit

Description of site: Tidelands along Purdy Spit containing a large number of polyvinyl chloride tubes used for protecting juvenile geoduck from predators

Reference: Thom et al. 2008

- *Why studied*: Evaluate effects of geoduck harvesting on eelgrass, evaluate whether best practices were followed.
- *When*: 2003-2007
- *Study looked at*: effects of tube removal and eelgrass cover inside and outside of tube field
- *Findings—eelgrass trends*: Geoduck aquaculture likely took place on an existing eelgrass patch, causing notable absence of eelgrass compared to surroundings.
- *Findings—eelgrass stressors*: Tubes in substrate disrupt natural rhizome growth, and anti-predator netting causes physical damage or shades out eelgrass when fouled. Some bare areas outside tube fields with no apparent explanation. Natural recovery might take up to 16 years, but replanting could accelerate recovery.

A.4 Eagle Harbor

Description of site: 0.6-acre transplant site near Washington State Department of Transportation facility and boat docks, near town and urban stream

Reference: Thom et al. 2001c

- *Why studied*: Monitoring of restoration/mitigation program for Department of Transportation facility
- *When*: 1998-2000
- *Study looked at*: Qualitative visits monitored eelgrass health, number of crab, and macroalgal cover. Quantitative visits recorded algal cover, crab and clam siphon holes, shoot density. Also monitored reference site.
- *Findings—eelgrass trends*: Survival of transplanted eelgrass very poor, mostly in deeper portions, absent by 2000. Reference site was well established and healthy during same interval.
- *Findings—eelgrass stressors*: Macroalgae, mooring chain scour (clear effects), bioturbation from crab (did not appear extensive). Note that macroalgal cover at reference site was always much lower, area better flushed by tides. Macroalgae thought to be primary, may be affected by nutrient input and weather. Localized but significant effects of boats (mooring, prop scour, grounding.)

A.5 Shaw Island

Description of site: Semi-protected cove south of Shaw Island; cable was embedded via machine in 1993.

Reference: Austin et al. 2004

- *Why studied*: Aftermath of submarine cable installation, referenced in broader paper about effects of cables
- *When*: 1993-2001
- *Study looked at*: eelgrass cover and sediment characteristics
- *Findings—eelgrass trends*: Linear scar from cable installation was not naturally recolonized due to anoxic sediment. After sediment remediation and transplanted, eelgrass recovered in 6years.
- *Findings—eelgrass stressors*: Direct damage and resulting anoxic sediment from submarine cable embedment killed eelgrass and inhibited recovery.

A.6 Port Townsend

Description of site: Port Townsend developed waterfront; a dock close to shore was replaced by a dock further from shore and with adaptations to reduce shading

Reference: Diefenderfer et al. 2005

- *Why studied*: Monitoring of eelgrass transplants following dock replacement at the Northwest Maritime Center, including reference site
- *When*: 2004
- *Study looked at*: eelgrass abundance, substrate type, macro-algae species and their percent cover, light data (photosynthetically active radiation) under dock.
- *Findings—eelgrass trends*: Too soon to tell ultimate recovery of eelgrass, but most transplants were successful only in deeper part of site
- *Findings—eelgrass stressors*: Removal of overwater structure was expected to allow transplanted eelgrass to survive in previously unoccupied/overshaded area, but macroalgae appeared to outcompete eelgrass in shallower portions of the plot.

A.7 Clinton Ferry Terminal

Description of site: Immediate vicinity of old Clinton ferry terminal, prior to upgrade

Reference: Thom et al 1997

- *Why studied*: determine impacts of ferry terminals and develop mitigation measures
- *When*: 1994
- *Study looked at*: eelgrass cover/density, irradiance, fish and macroinvertebrates in eelgrass plots, current speeds during ferry dockings, light enhancement technologies
- *Findings—eelgrass trends*: Clear absence of eelgrass within 5 m of terminal and within propeller wash zone
- *Findings—eelgrass stressors*: Shading from dock, though light was relatively high around edges where eelgrass absent. Modification of sediment during original construction possibly affects eelgrass, as

well as maintenance activities. Seastar foraging and crab burrowing disrupts eelgrass, both populations enhanced by pilings. Propellers scour sediments and reduce light availability.

A.8 Lincoln Park

Description of site: Armored shoreline with fill placed in 1988 to protect seawall. Eelgrass was transplanted in 1993 into areas previously observed to be occupied by eelgrass.

Reference: Antrim et al 1993

- *Why studied*: Assess impacts on marine biota of fill placement to protect seawall
- *When*: 1993, compared with studies done in 1985-1990
- *Study looked at*: Patch shape, size, density, substrate, tidal elevation
- *Findings—eelgrass trends*: Eelgrass generally exists within narrow bounds on sandy substrate, sparser where cobble occurs. Not all eelgrass patches found pre-fill (1985) were found in 1993, but healthy eelgrass did occur where it had not occurred before.
- *Findings—eelgrass stressors*: High wave energy in area may contribute to presumed high natural annual variability in eelgrass. Unclear if changes are related to introduction of coarser substrate from the beach fill. Recreational clam digging may have small effect, but most eelgrass is too deep to be affected.
- *Conclusion*: Eelgrass appears to remain viable, distribution appears to be limited by lack of suitable substrate.

A.9 Ediz Hook

Description of site: Sand placed over dense wood debris, planted with eelgrass

Reference: Pentec Environmental 2001

- *Why studied*: Monitoring of eelgrass transplants
- *When*: 1998-2001
- *Study looked at*: Success of transplants, as well as effect of fertilization treatment, organic carbon in sediment, and blade length at time of planting
- *Findings—eelgrass trends*: 40% survival after first year, small losses after but bed was expanding and appeared healthy
- *Findings—eelgrass stressors*: Proposed that initial loss could have been influenced by light limitation due to weather, as climatic conditions were better on the second year

A.10 Semiahmoo Bay

Description of site: Broad sand flat with moderate to dense eelgrass stands, area graveled for clam production though limited recreational use, no evidence of harvesting or disturbance at time of study.

Reference: Thom et al 1994

- *Why studied*: Graveling of mud and sand flats to increase clam production will affect biotic community including eelgrass.
- *When*: Study conducted in 1991, when sites had been graveled for at least 5 years
- *Study looked at*: percent cover of plants and animals, productivity and nutrient flux
- *Findings—eelgrass trends*: Eelgrass dominant on control (sand) plots, implied absent on control plots
- *Findings—eelgrass stressors*: Eelgrass is unable to survive on graveled substrates.

A.11 Ruston Way, Commencement Bay

Description of site: Shoreline was historic site of over 30 lumber mills operating between 1869 and 1977.

Reference: Elliott et al 2006

- *Why studied*: To examine whether wood waste creates harmful sediment conditions, and whether bacterial mats are indicators of these conditions.
- *When*: Study date not specified, published in 2006
- *Study looked at*: Eelgrass presence and cover in subtidal and intertidal, *Beggiota* presence, porewater sulfides and presence and depth of wood waste in sediment.
- *Findings—eelgrass trends*: Highest eelgrass densities located away from former lumber mills; intertidal presence only away from lumber mills
- *Findings—eelgrass stressors*: Wood waste and resulting sulfides reduces eelgrass cover in the subtidal and essentially excludes it from the intertidal.

A.12 Armitage Bay, Blakely Island

Description of site: Large eelgrass meadow with naturally occurring substantial ulvoid blooms during summer (no significant anthropogenic eutrophication).

Reference: Nelson and Lee 2001

- *Why studied*: To determine whether ulvoids reduce eelgrass density
- *When*: 1999-2000
- *Study looked at*: Eelgrass shoot density in midbed control (no ulvoid competition), edge control (naturally occurring ulvoid blooms), and removal treatments.
- *Findings—eelgrass trends*: Eelgrass density highest in midbed, lowest in edge controls. Ulvoid removal increases density but not to midbed levels; this may be because of difficulty of completely removing algae.

- *Findings—eelgrass stressors*: Competition with naturally occurring ulvoid blooms can reduce eelgrass density, probably through light reduction and possible physical intereference. The algae appeared unable to compete with dense eelgrass, suggesting possible positive feedback.

A.13 Hood Canal

Description of site: Surveyed most of Hood Canal, which representative focal areas chosen to cover range of beach setting and level of shoreline development

Reference: Simenstad et al. 2008

- *Why studied*: To determine effect of shoreline geomorphology and anthropogenic shoreline modifications on eelgrass landscape patterns
- *When*: 2000
- *Study looked at*: Eelgrass and green algae cover; presence of armoring; beach width, slope, relief, and drainage area
- *Findings—eelgrass trends*: No clear connection between eelgrass metrics and shoreline armoring in less armored focal areas, but in the most developed focal areas with the most armoring, eelgrass density was significantly higher in the unarmored portions
- *Findings—eelgrass stressors*: Effect of armoring may only be notable over a threshold. Study did not determine whether armoring contributed to differences in shoreline geomorphology that then would appear to better explain eelgrass distribution.

A.14 Fisk Bar, Samish Bay

Description of site: Geoduck farm adjacent to eelgrass beds. Eelgrass invaded the farmed zone after geoduck culture began in 2002.

Reference: University of Washington 2011

- *Why studied*: To determine effect of geoduck aquaculture and harvest on eelgrass
- *When*: 2008-2010
- *Study looked at*: Eelgrass density, size, flowering rate, underground branching
- *Findings—eelgrass trends*: Reduction in shoot density, flowering rate, size, and branching activity following eelgrass harvest.
- *Findings—eelgrass stressors*: Reduced light levels from macroalgal growth on predator exclusion nets contributed to eelgrass decline; substrate disturbance may contribute. Some preliminary evidence for spillover effects.

Appendix B

Maps and Supporting Data for Spatial Stressor Analysis

Appendix B

Maps and Supporting Data for Spatial Stressor Analysis

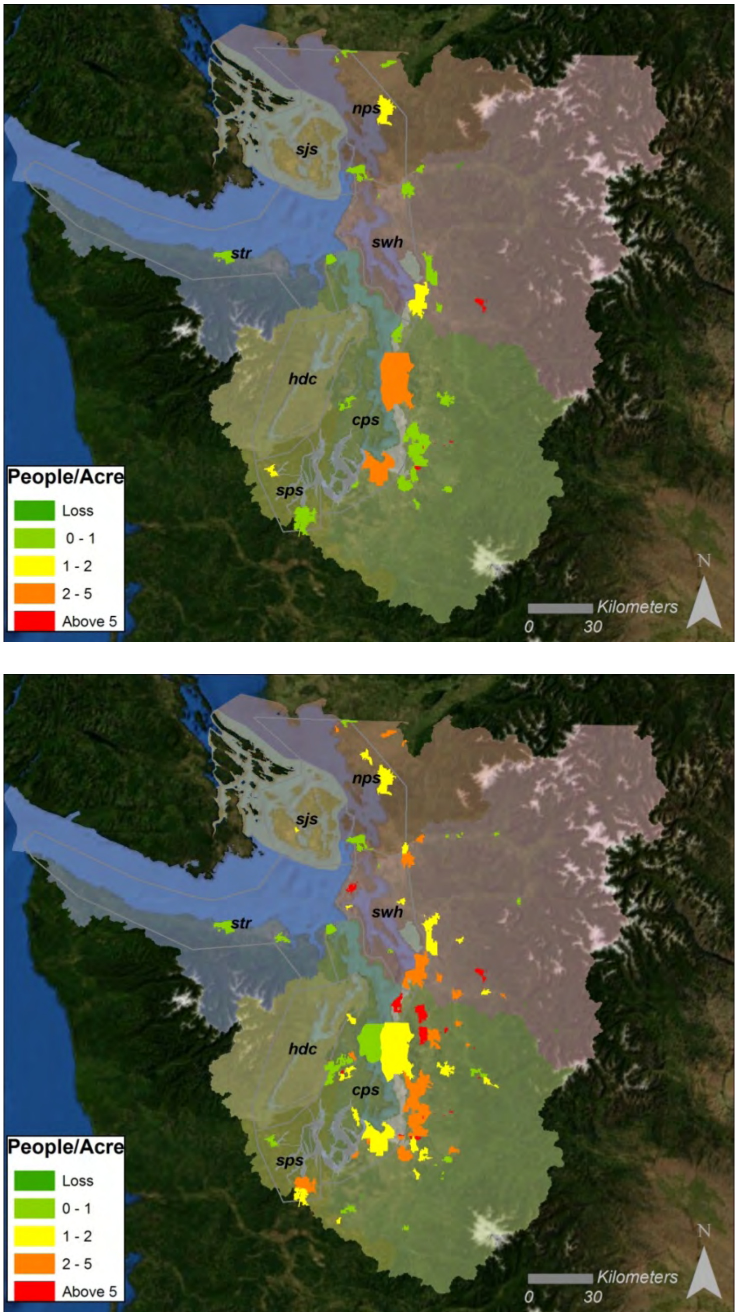


Figure B.1. Population Density Changes 1900 to 1950 (Above) and 1950 to 2000 (Below) for Urban Growth Areas in the U.S. Puget Sound Watershed. Most urban areas experienced a greater rate of growth from 1950 to 2000, and more cities had been incorporated by the second half of the twentieth century. Many growth areas were in the drainage area for the Central Puget Sound sampling area.

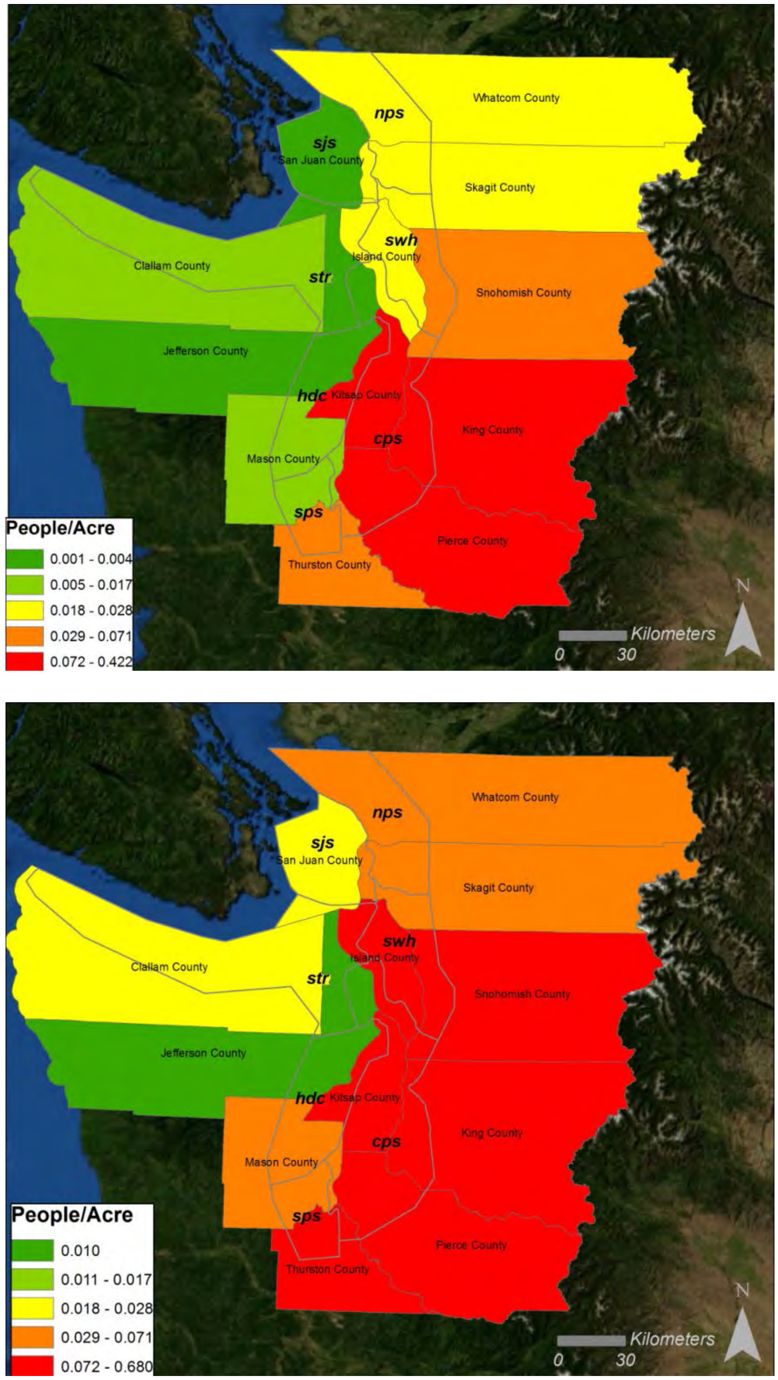


Figure B.2. Population Density Changes 1900 to 1950 (Above) and 1950 to 2000 (Below) for Puget Sound Counties. During the first half of the twentieth century, growth was concentrated in and around the Central Puget Sound Sampling area. By the second half of the century, Whidbey Island and South and North Puget Sound were experiencing increased growth. Hood Canal has had the lowest rate of growth.

B.1 Watershed Development

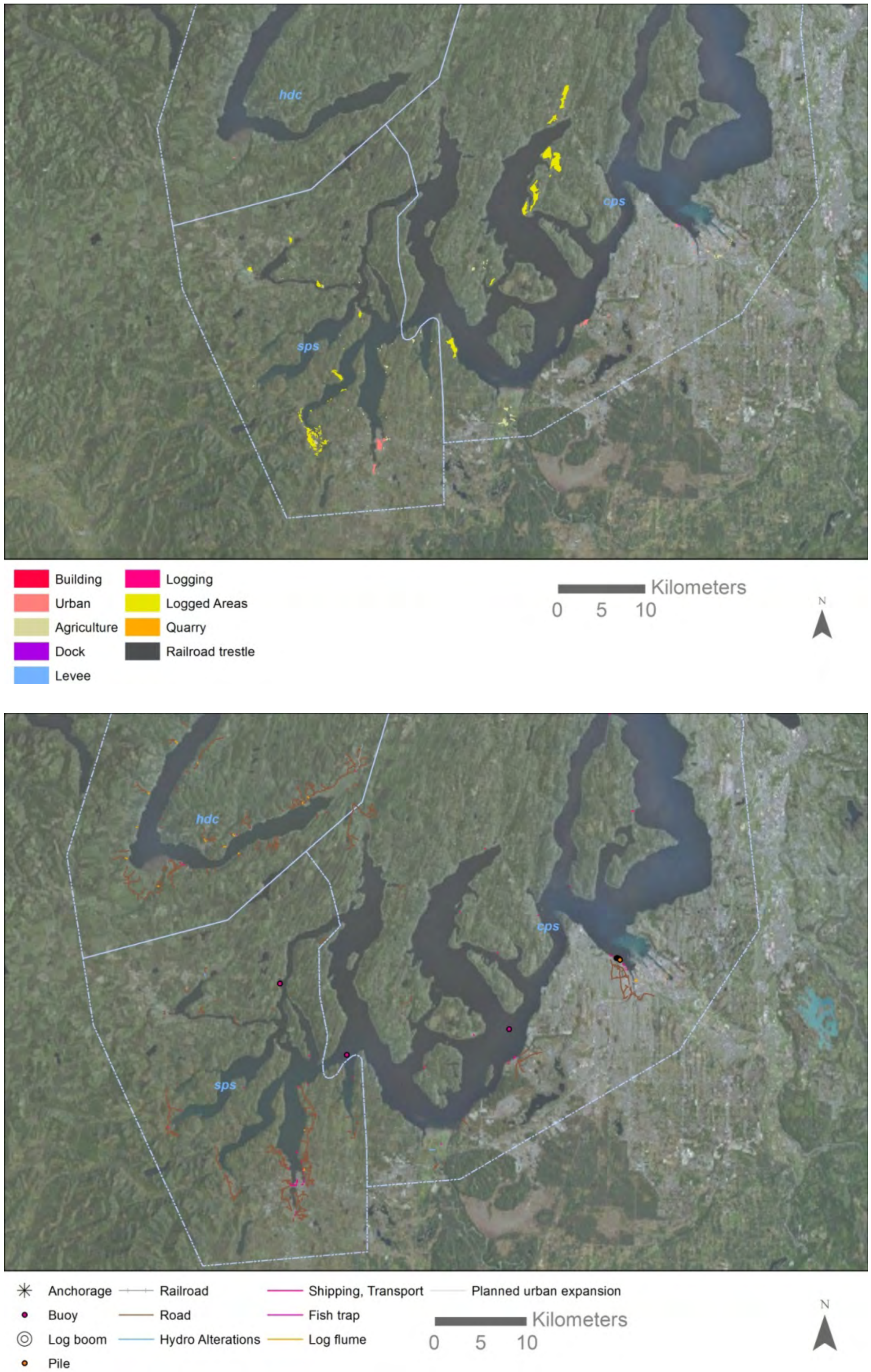


Figure B.3. Land-Use Information from 1880s – South Puget Sound Assessment Region

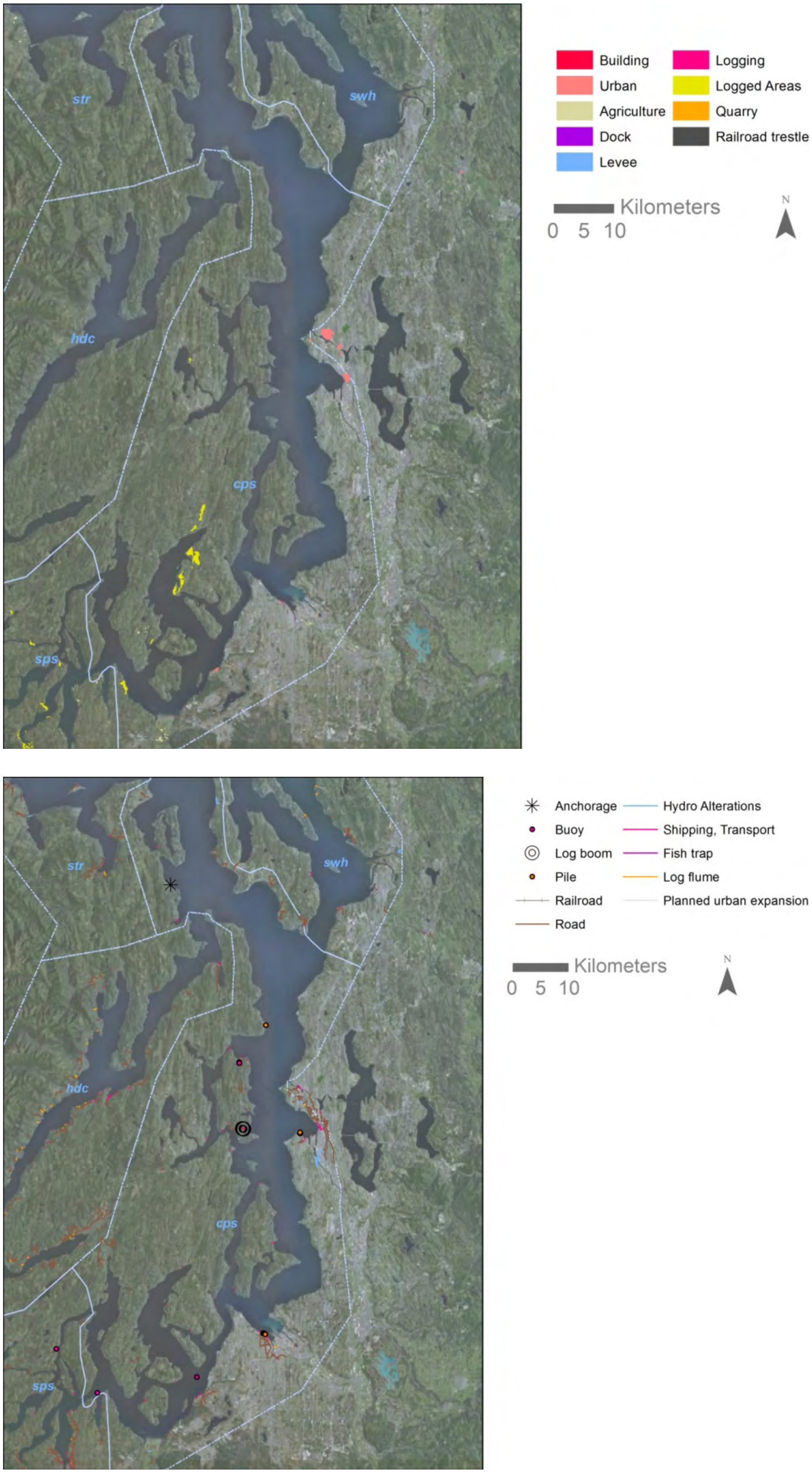


Figure B.4. Land-Use Information 1880s – Central Puget Sound Assessment Region

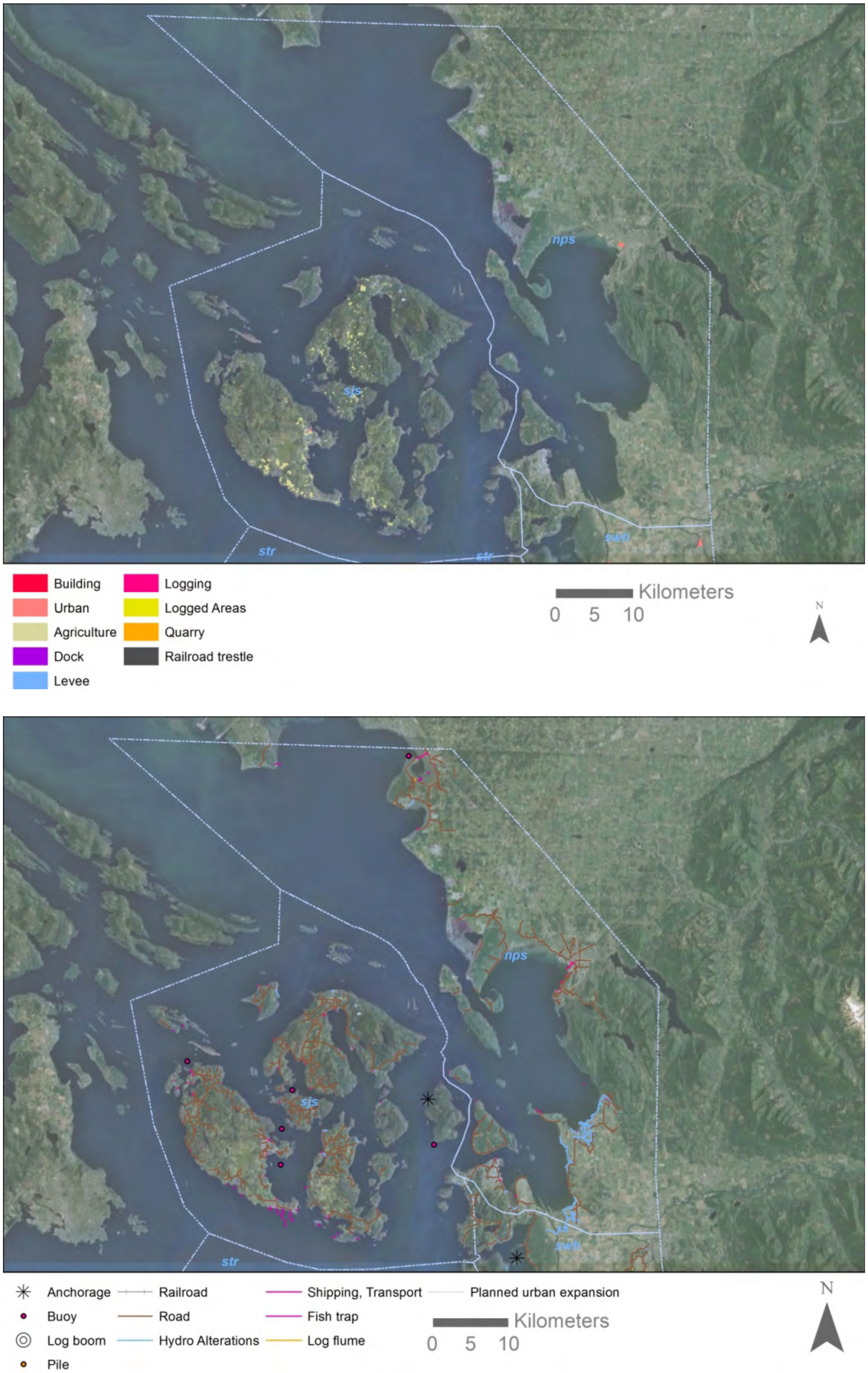


Figure B.5. Land-Use Information 1880s – North Puget Sound and San Juan Assessment Regions

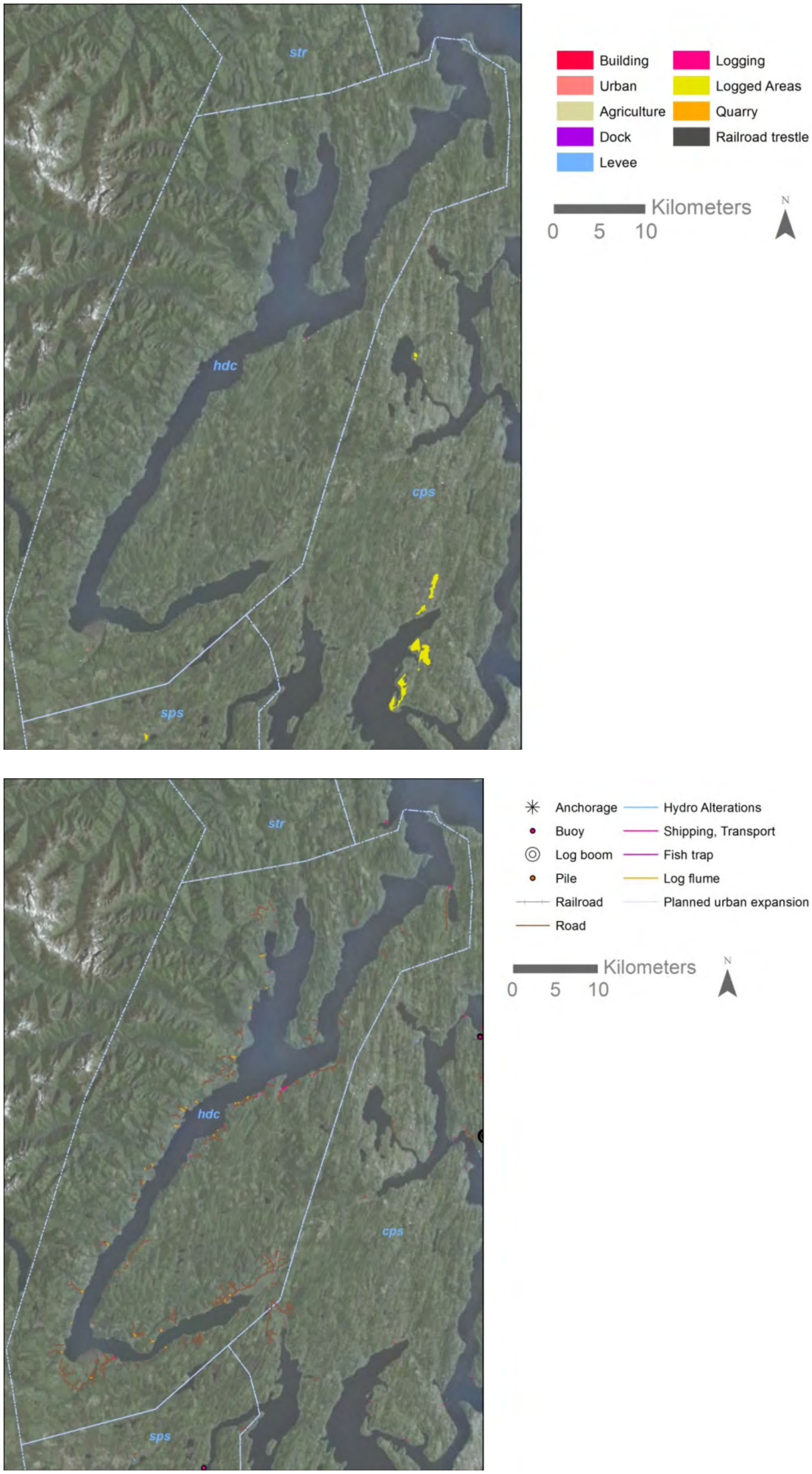


Figure B.6. Land-Use Information 1880s – Hood Canal Assessment Region

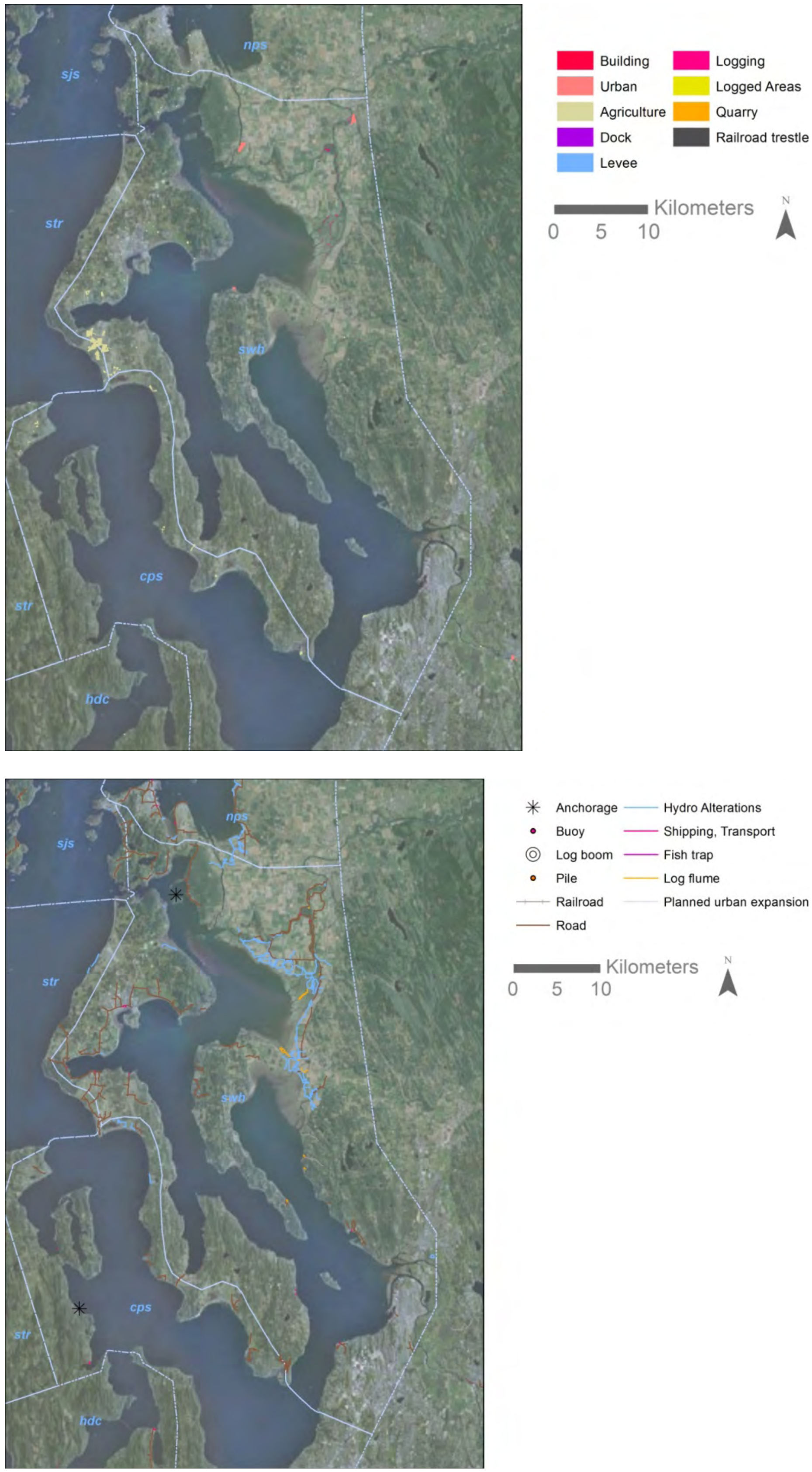
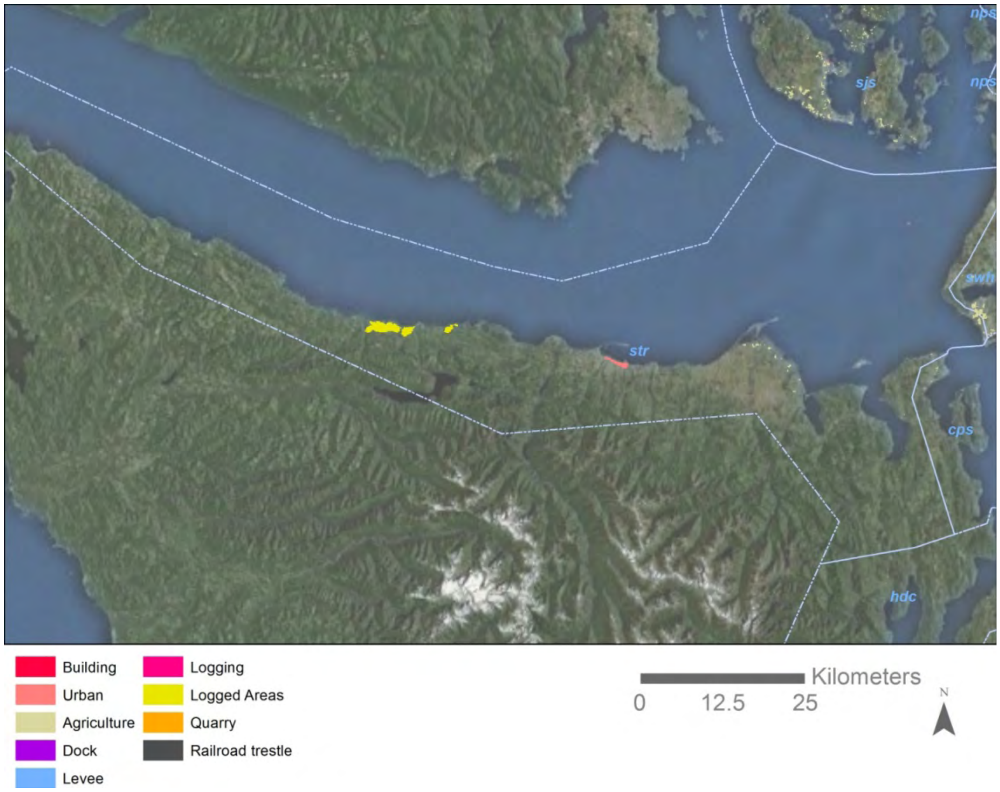


Figure B.7. Land-Use Information, 1880s – Saratoga-Whidbey Assessment Region



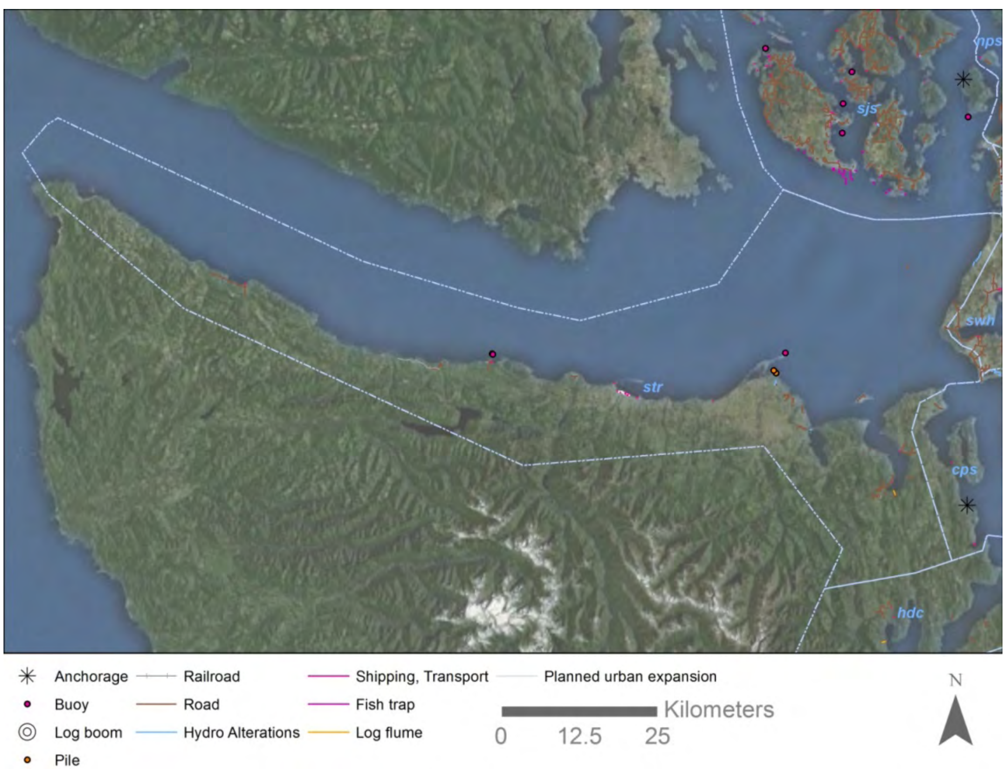


Figure B.8. Land-Use Information, 1880s – Straits Assessment Region

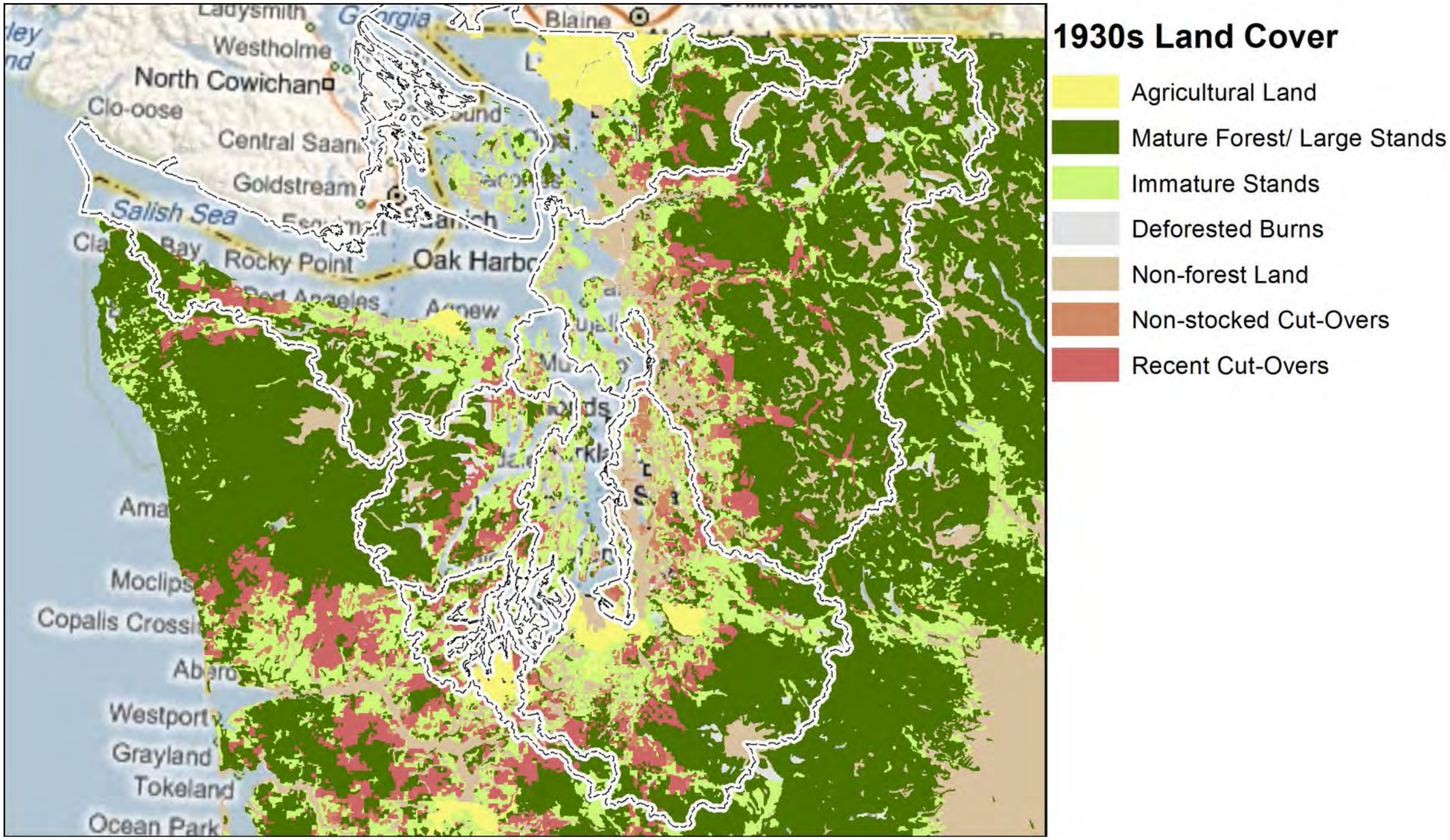


Figure B.9. Forest Cover in the 1930s. Agriculture areas in Nooksack, Deschutes, Dungeness, and Puyallup. Non-forested areas in North Puget Sound, Central Puget Sound, Saratoga-Whidbey, and South Puget Sound. Logged areas present in all watersheds.

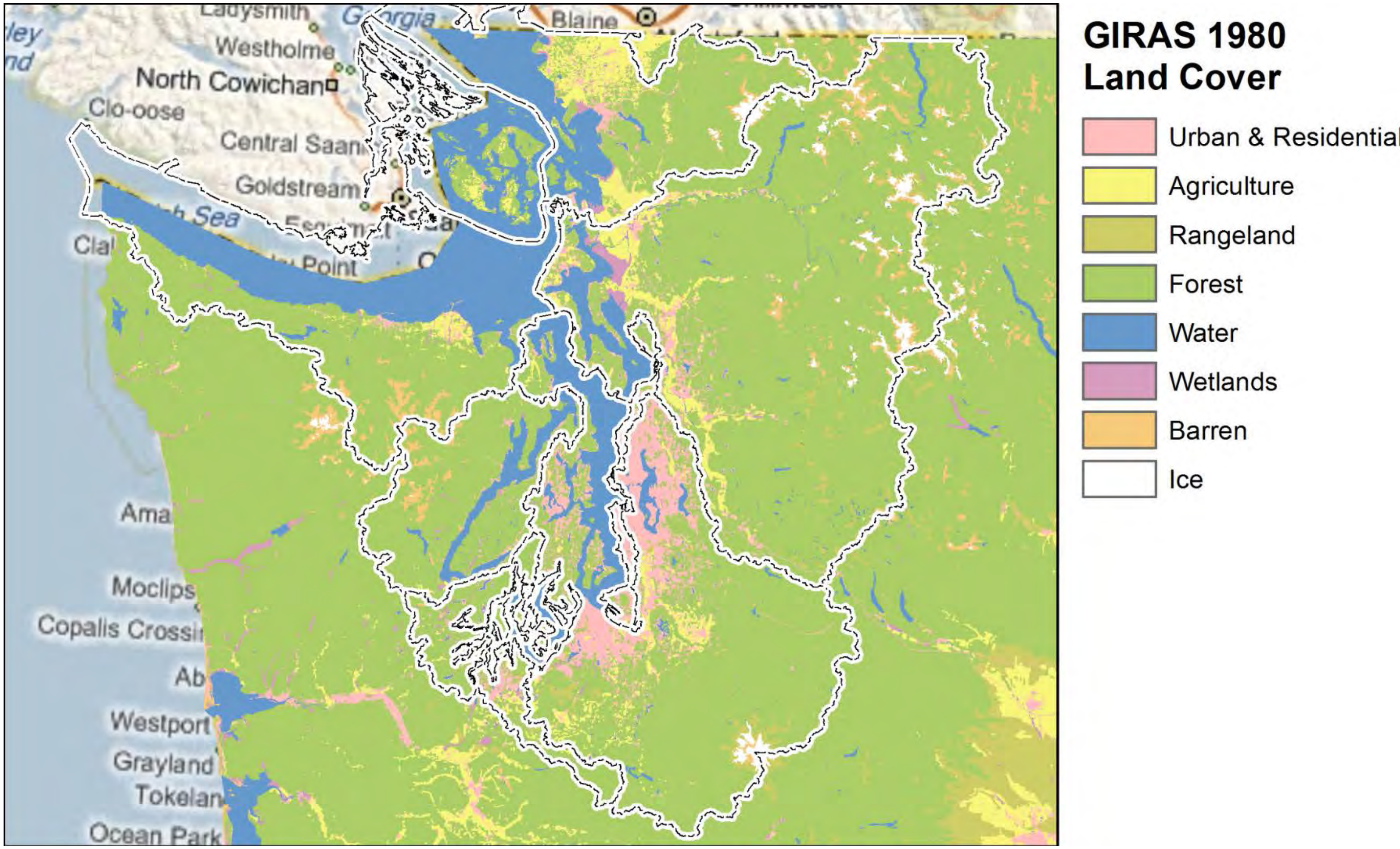


Figure B.10. GIRAS Land Cover Dataset Circa 1980

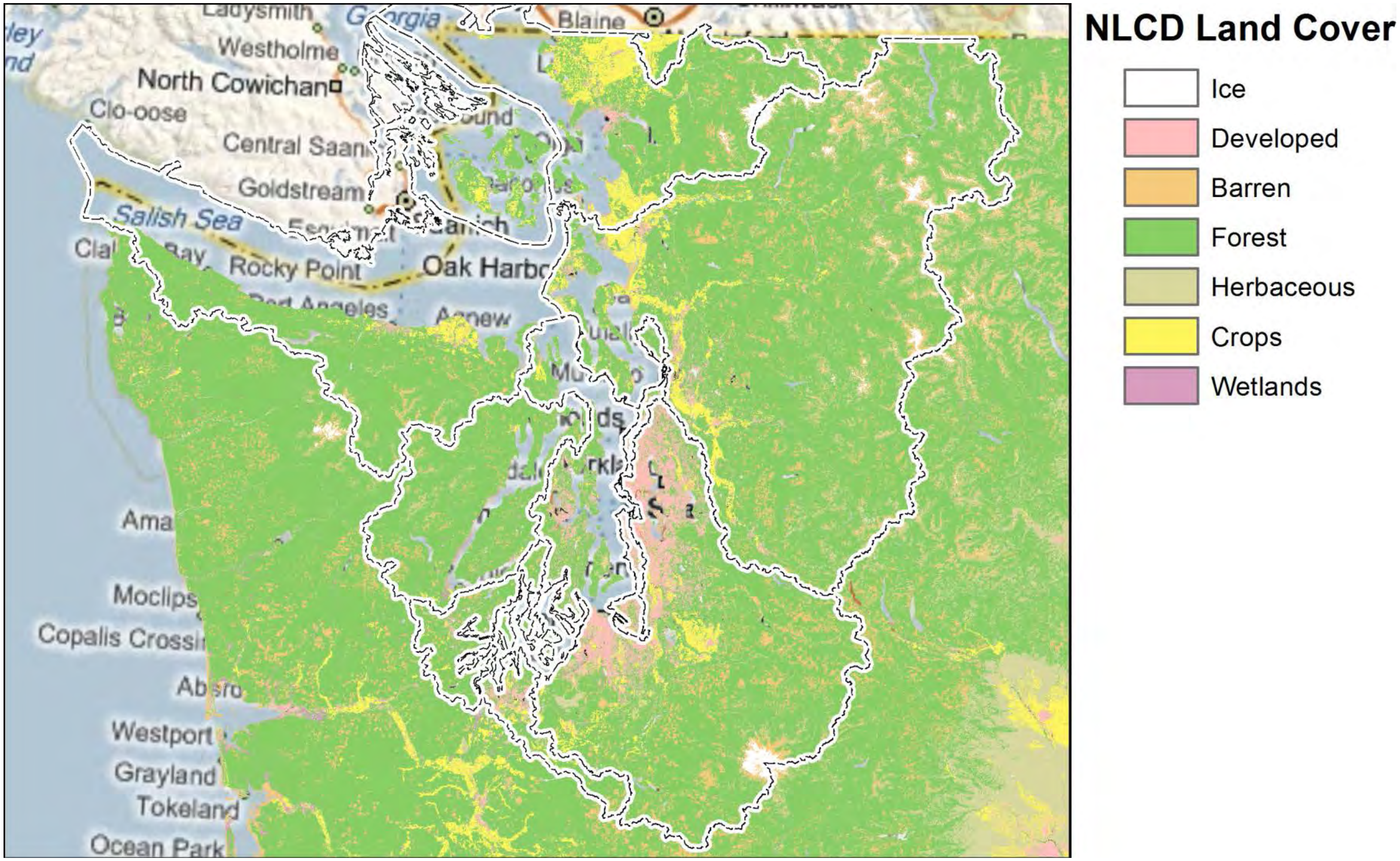


Figure B.11. 2001 Land Use/Land Cover, USGS, Reclassified into High-Level Categories for Cross-Comparison Between Years

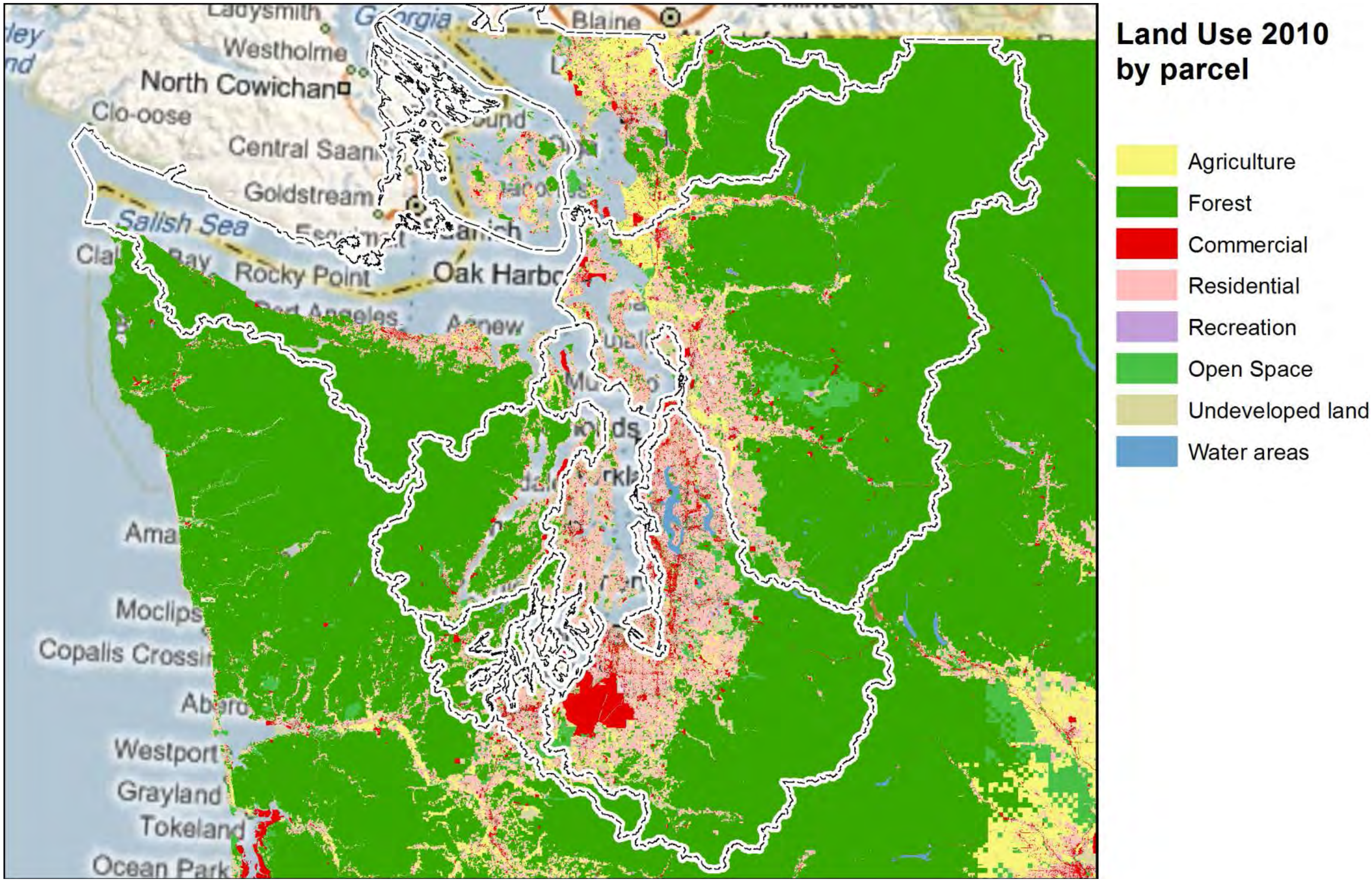


Figure B.12. Land Use (2010) by Parcel Type. Reclassified for cross-comparison between years.

Table B.1. Percent Impervious Surface by HUC 10 Watershed

HUC ID	HUC Name	ACRES	Percent Impervious Surface			
			1980 (V1)	1980 (V2)	1992	2001
		Central Puget Sound				
1711001201	Cedar River	112953	2.12	3.05	3.48	4.77
1711001202	Lake Sammamish	64575	5.29	8.07	7.57	10.83
1711001203	Middle Sammamish River	90621	11.19	16.81	17.19	23.58
1711001204	Lower Sammamish River	113941	17.60	24.76	24.76	30.90
1711001301	Upper Green River	86632	1.06	1.06	0.09	0.59
1711001302	Middle Green River	86355	1.36	1.41	0.24	0.87
1711001303	Lower Green River	144211	12.51	15.94	17.90	22.28
1711001401	Carbon River	146539	0.34	0.48	0.56	1.40
1711001402	Upper Puyallup River	117185	0.32	0.42	0.48	1.45
1711001403	Upper White River	186979	0.08	0.11	0.11	0.45
1711001404	Lower White River	130508	2.40	2.98	3.37	5.53
1711001405	Lower Puyallup River	49080	9.96	15.14	17.55	24.43
1711001501	Upper Nisqually River	185462	0.20	0.21	0.16	0.57
1711001502	Middle Nisqually River	126909	0.39	0.32	0.27	1.30
1711001503	Lower Nisqually River-Frontal Puget Sound	180362	2.94	2.93	2.44	4.15
1711001903	Chambers Creek-Frontal Puget Sound	106266	17.21	22.49	19.51	28.62
1711001904	Anderson Island-Hartstene Island	67046	3.53	5.63	4.55	4.27
1711001907	Ollala Valley-Frontal Puget Sound	184555	4.83	7.49	8.61	9.76
1711001908	Chimacum Creek-Frontal Port Ludlow	51337	4.04	4.81	2.57	4.17
1711001910	Port Orchard Sound	22530	1.47	2.07	0.67	0.54
1711001912	Puget Sound	248324	0.51	0.62	0.23	0.27
		Hood Canal				
1711001701	South Fork Skokomish River	66237	0.06	0.05	0.10	0.64
1711001702	North Fork Skokomish River-Skokomish River	90541	0.21	0.24	0.16	0.50
1711001801	Tahuya River-Frontal Hood Canal	157341	1.78	2.53	1.95	2.40
1711001802	Jefferson Creek-Hamma Hamma River	53747	0.01	0.00	0.02	0.20
1711001803	Lilliwaup Creek-Frontal Hood Canal	49533	0.49	0.76	0.41	0.71
1711001804	Duckabush River	48918	0.05	0.08	0.05	0.15
1711001805	Dosewallips River	73806	0.05	0.09	0.06	0.14
1711001806	Big Quilcene River	43748	0.24	0.39	0.17	0.35
1711001807	Little Quillcene River-Frontal Hood Canal	84461	0.55	1.00	0.57	0.91
1711001808	Hood Canal	96097	0.18	0.30	0.12	0.06
		North Puget Sound				
1711000201	Point Roberts-Frontal Strait of Georgia	2874	3.30	4.52	3.46	9.83
1711000202	California Creek-Frontal Semiahmoo Bay	57183	5.95	5.21	3.45	6.23
1711000203	Samish River	73991	2.58	2.49	1.53	2.56
1711000204	Telegraph Slough-Frontal Padilla Bay	56912	6.44	5.64	4.11	7.39
1711000205	Lummi Island-Guemes Island	14414	0.77	0.98	0.61	1.15
1711000206	Padilla Bay-Strait of Georgia	383256	0.03	0.04	0.06	0.04
1711000401	Upper North Fork Nooksack River	123549	0.03	0.05	0.01	0.45
1711000402	Lower North Fork Nooksack River	64554	0.28	0.38	0.33	0.80

Table B.1. (contd)

HUC ID	HUC Name	ACRES	Percent Impervious Surface			
			1980 (V1)	1980 (V2)	1992	2001
		North Puget Sound				
1711000403	Middle Fork Nooksack River	63601	0.03	0.05	0.03	0.29
1711000404	South Fork Nooksack River	118766	0.22	0.20	0.08	0.47
1711000405	Nooksack River	29553	1.34	1.40	0.62	1.48
1711000405	Nooksack River-Frontal Bellingham Bay	107851	4.87	3.60	2.38	5.47
1711000406	Whatcom Creek-Frontal Bellingham Bay	76423	5.15	7.14	5.92	8.92
1711000407	Bellingham Bay	40308	0.33	0.28	0.17	0.15
		Puget Sound, Across Sampling Regions				
1711001902	Lunds Gulch-Frontal Puget Sound	110331	18.68	24.68	24.76	32.53
1711001909	South Puget Sound	111662	0.35	0.59	0.15	0.13
		San Juan				
1711000301	Orcas Island	46527	1.10	1.42	0.93	2.27
1711000302	Lopez Island	26149	1.65	1.38	1.34	2.17
1711000303	San Juan Island	39458	1.82	1.18	1.71	3.26
1711000305	Haro Strait-Strait of Georgia	474478	0.02	0.04	0.01	0.02
		South Puget Sound				
1711001601	Upper Deschutes River	57469	0.16	0.13	0.41	1.22
1711001602	Lower Deschutes River	51180	5.57	6.80	7.36	10.22
1711001905	McLane Creek-Frontal Puget Sound	68873	7.50	10.94	9.64	11.13
1711001906	Goldsborough Creek-Frontal Puget Sound	216003	1.37	1.95	1.77	2.33
		Straits				
1711001913	Rosario Strait-Strait of Juan De Fuca	75023	0.03	0.05	0.08	0.03
1711002001	Snow Creek-Frontal Discovery Bay	51955	1.53	2.06	1.39	2.28
1711002002	Jimmycomelately Creek-Frontal Sequim Bay	43528	1.66	1.52	2.11	6.36
1711002003	Dungeness River	127036	0.45	0.32	0.51	1.49
1711002004	Morse Creek-Frontal Port Angeles Harbor	102899	2.06	2.34	2.41	4.44
1711002005	Elwha River	205810	0.03	0.04	0.07	0.13
1711002007	Discovery Bay-Strait of Juan De Fuca	452653	0.04	0.04	0.02	0.02
1711002101	Lyre River	42968	0.16	0.29	0.14	0.29
1711002102	Salt Creek-Frontal Strait of Juan De Fuca	61506	0.36	0.43	0.17	0.52
1711002103	Pysht River-Frontal Strait of Juan De Fuca	141233	0.18	0.23	0.11	0.32
1711002105	Port San Juan-Strait of Juan De Fuca	554367	0.00	0.01	0.00	0.00
		Saratoga-Whidbey				
1711000501	Three Fools Creek-Lightning Creek	72480	0.00	0.00	0.00	0.00
1711000502	Ruby Creek	138682	0.00	0.00	0.24	0.33
1711000503	Ross Lake-Skagit River	173238	0.01	0.00	0.00	0.00
1711000504	Gorge Lake-Skagit River	156249	0.04	0.06	0.09	0.16
1711000505	Diobsud Creek-Skagit River	85844	0.04	0.05	0.06	0.26
1711000506	Cascade River	118530	0.01	0.00	0.03	0.22
1711000507	Baker River	190444	0.04	0.05	0.05	0.25
1711000508	Illabot Creek-Skagit River	90841	0.18	0.24	0.13	0.61
1711000601	Upper Sauk River	153138	0.00	0.01	0.01	0.11
1711000602	Upper Suiattle River	118026	0.00	0.00	0.00	0.01

Table B.1. (contd)

HUC ID	HUC Name	ACRES	Percent Impervious Surface			
			1980 (V1)	1980 (V2)	1992	2001
		Saratoga-Whidbey				
1711000603	Lower Suiattle River	102265	0.00	0.00	0.01	0.25
1711000604	Lower Sauk River	95265	0.40	0.46	0.29	0.86
1711000701	Finney Creek-Skagit River	176550	0.69	0.79	0.42	1.02
1711000702	Skagit River-Frontal Skagit Bay	113160	4.28	4.04	2.98	5.96
1711000801	North Fork Stillaguamish River	182260	0.27	0.30	0.13	0.61
1711000802	South Fork Stillaguamish River	162343	0.39	0.54	0.41	0.88
1711000803	Stillaguamish River-Frontal Port Susan	104821	2.69	2.87	2.21	4.01
1711000901	Tye River	86875	0.00	0.00	0.12	0.52
1711000902	Beckler River	64586	0.00	0.00	0.04	0.59
1711000903	South Fork Skykomish River	79562	0.02	0.03	0.06	0.53
1711000904	North Fork Skykomish River	93924	0.01	0.02	0.07	0.17
1711000905	Sultan River	67158	0.11	0.12	0.13	0.51
1711000906	Wallace River-Skykomish River	75083	0.56	0.67	0.60	1.58
1711000907	Woods Creek-Skykomish River	66905	1.26	1.34	1.45	2.45
1711001001	North Fork Snoqualmie River	65908	0.05	0.07	0.06	0.77
1711001002	Middle Fork Snoqualmie River	109478	0.10	0.13	0.11	0.21
1711001003	South Fork Snoqualmie River	55458	4.45	4.84	2.06	2.81
1711001004	Upper Snoqualmie River	90422	2.01	2.33	1.36	2.32
1711001005	Tolt River	62609	0.04	0.05	0.10	0.72
1711001006	Lower Snoqualmie River	60231	1.80	1.56	1.43	3.24
1711001101	Pilchuck River	87769	1.82	3.01	3.18	4.42
1711001102	Quilceda Creek-Frontal Possession Sound	98863	9.69	11.66	8.50	14.13
1711001901	Whidbey Island	151102	4.83	6.12	4.61	6.97
1711001911	Skagit Bay-Whidbey Basin	156935	0.30	0.40	0.20	0.12

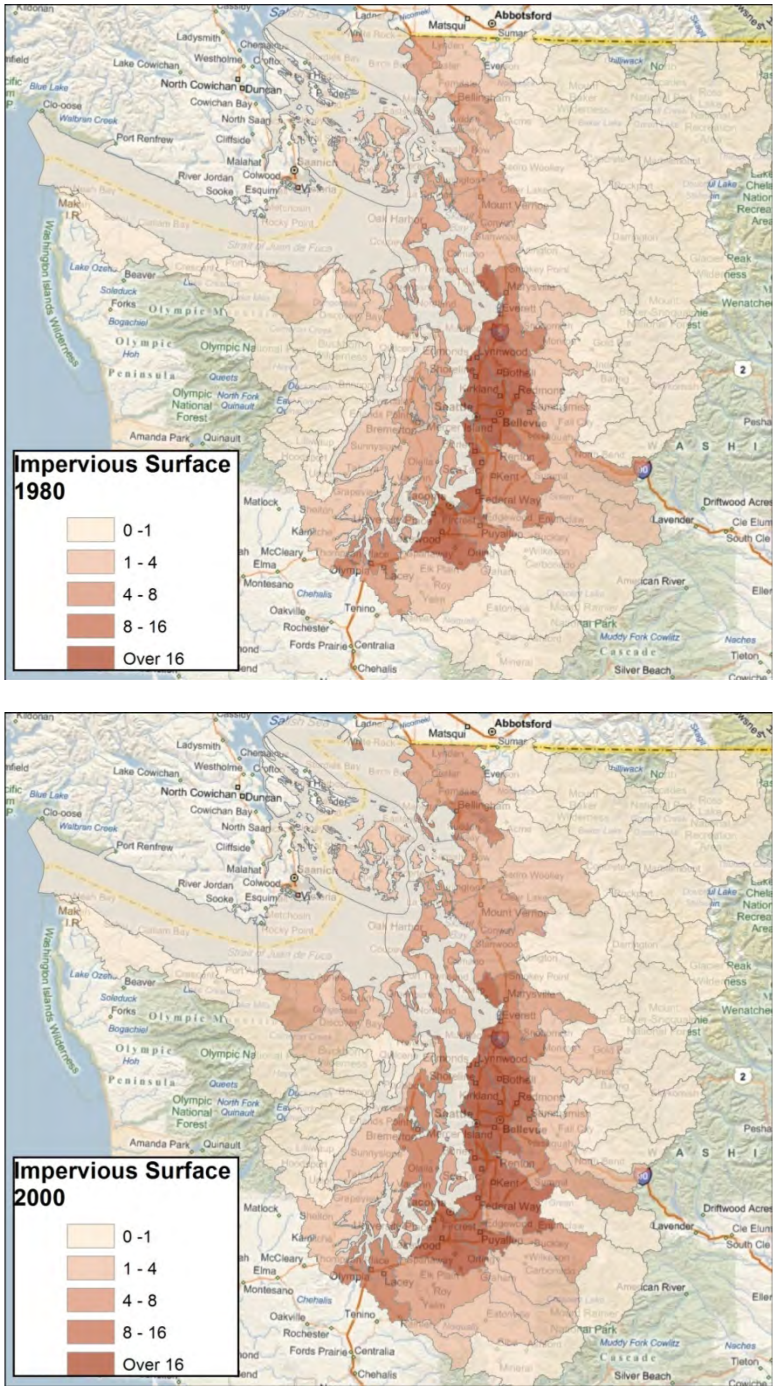


Figure B.13. Impervious Surface Estimates (% Impervious) per HUC 10 Watersheds for 1980 (Above) and 2001(Below)

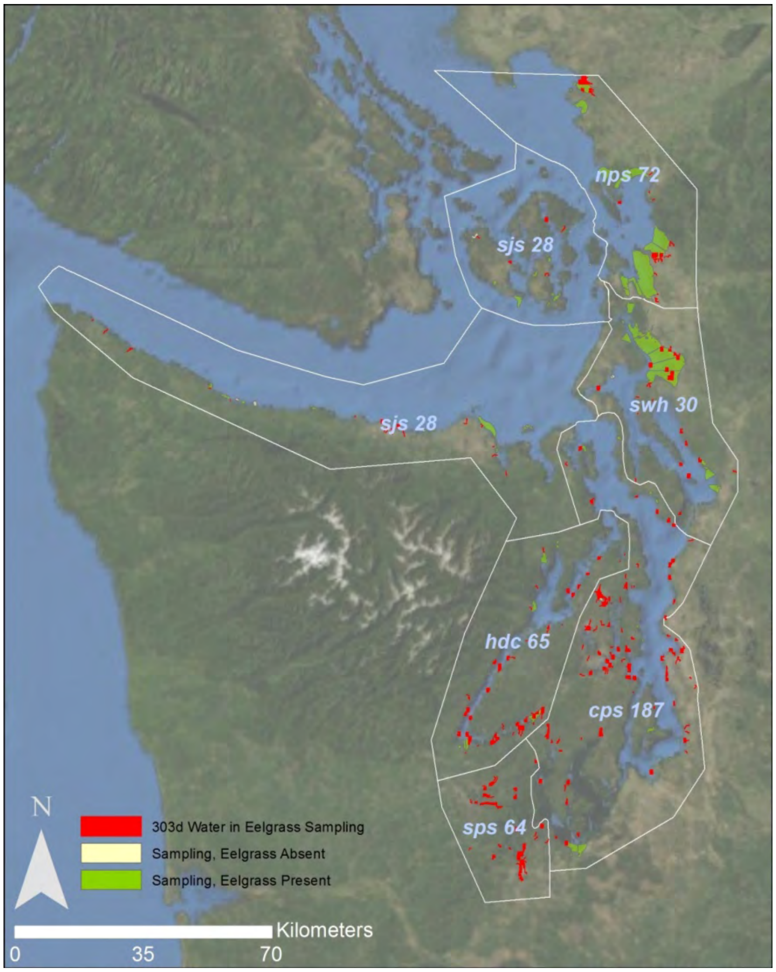


Figure B.14. 303(d) Water Quality – Category 5 Near (<300 ft.) Eelgrass Sampling Polygons. Though eelgrass presence/absence in smaller units may not be distinguishable at this scale, it is evident that many of the contaminated areas co-occur with eelgrass meadows.

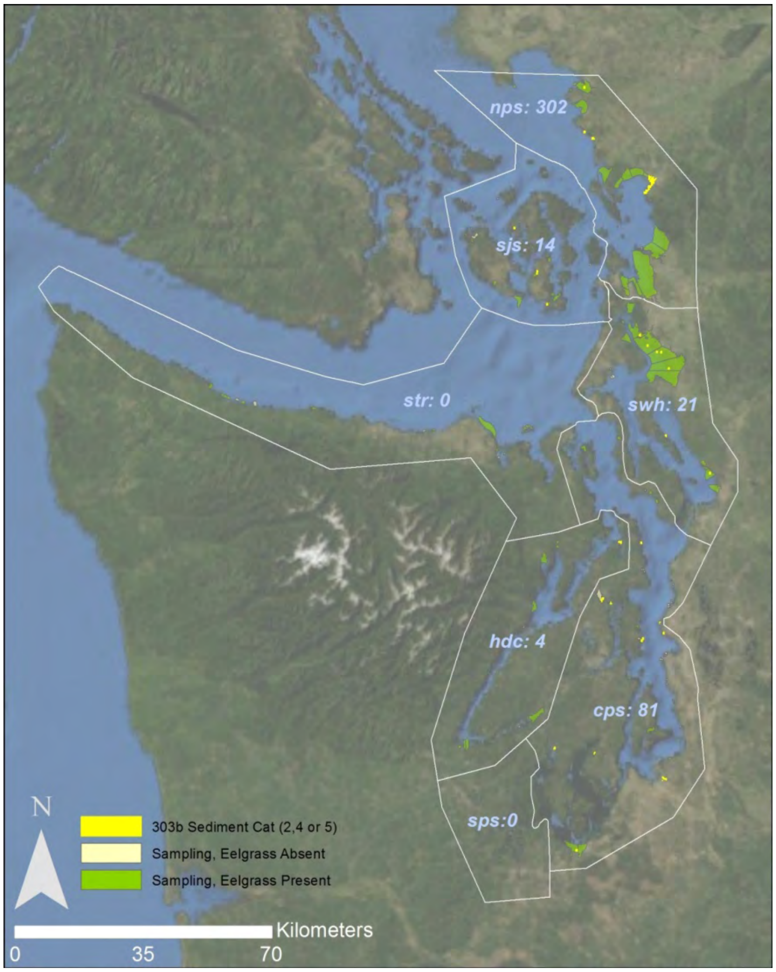


Figure B.15. 305b Sediment Contaminants Identified In Survey Areas. Though eelgrass presence/absence in smaller units may not be distinguishable at this scale, it is evident that many of the contaminated areas co-occur with eelgrass meadows.

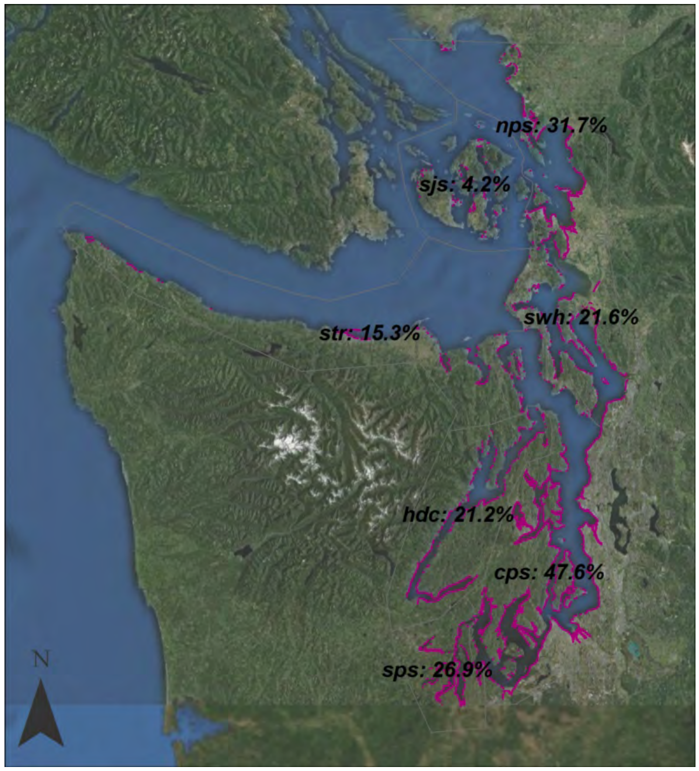


Figure B.16. Percent of Shoreline That Is Armored Per Regional Assessment Unit. Armored shorelines shown in purple on map.

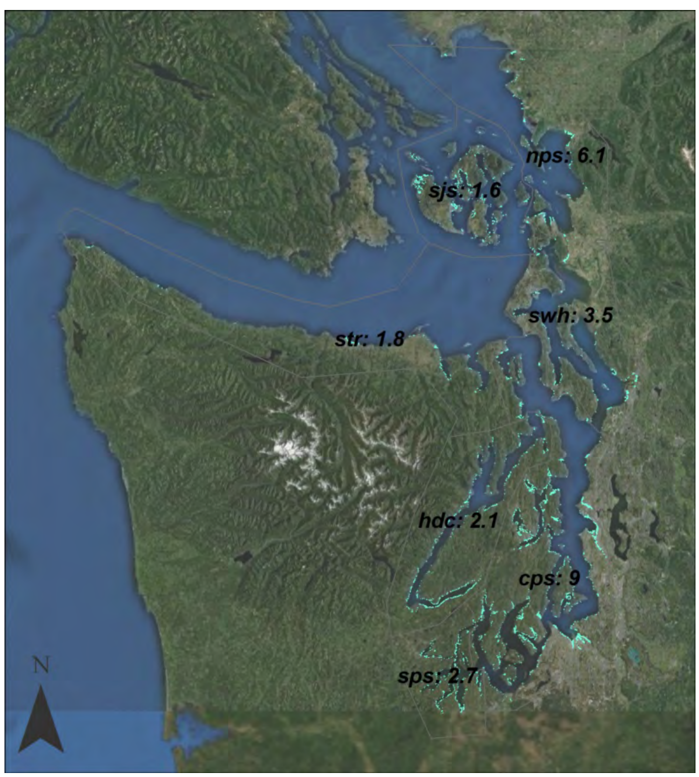


Figure B.17. Overwater Structure Area (ft^2) Per Linear Foot of Shoreline in Regional Assessment Units. Overwater structures shown in turquoise.

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